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Fruehling et al.

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(54) **METHODS AND APPARATUS FOR INCREASING EFFICIENCY AND OPTICAL BANDWIDTH OF A MICROELECTROMECHANICAL SYSTEM PISTON-MODE SPATIAL LIGHT MODULATOR**

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(51) **Int. Cl.**

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G02B 26/06	(2006.01)
G02B 26/08	(2006.01)
G09G 3/34	(2006.01)

(52) **U.S. Cl.**
CPC ***G02B 26/06*** (2013.01); ***G02B 26/0833*** (2013.01); ***G02B 26/0841*** (2013.01); ***G09G 3/3466*** (2013.01); *B81B 2201/04* (2013.01)

(58) **Field of Classification Search**
CPC G02B 26/0841; G02B 26/0833; G02B 26/001; G02B 26/06; G02B 27/425; G02B 5/09; G02B 7/1821
USPC 359/237, 265–267, 290–292, 295, 298
See application file for complete search history.

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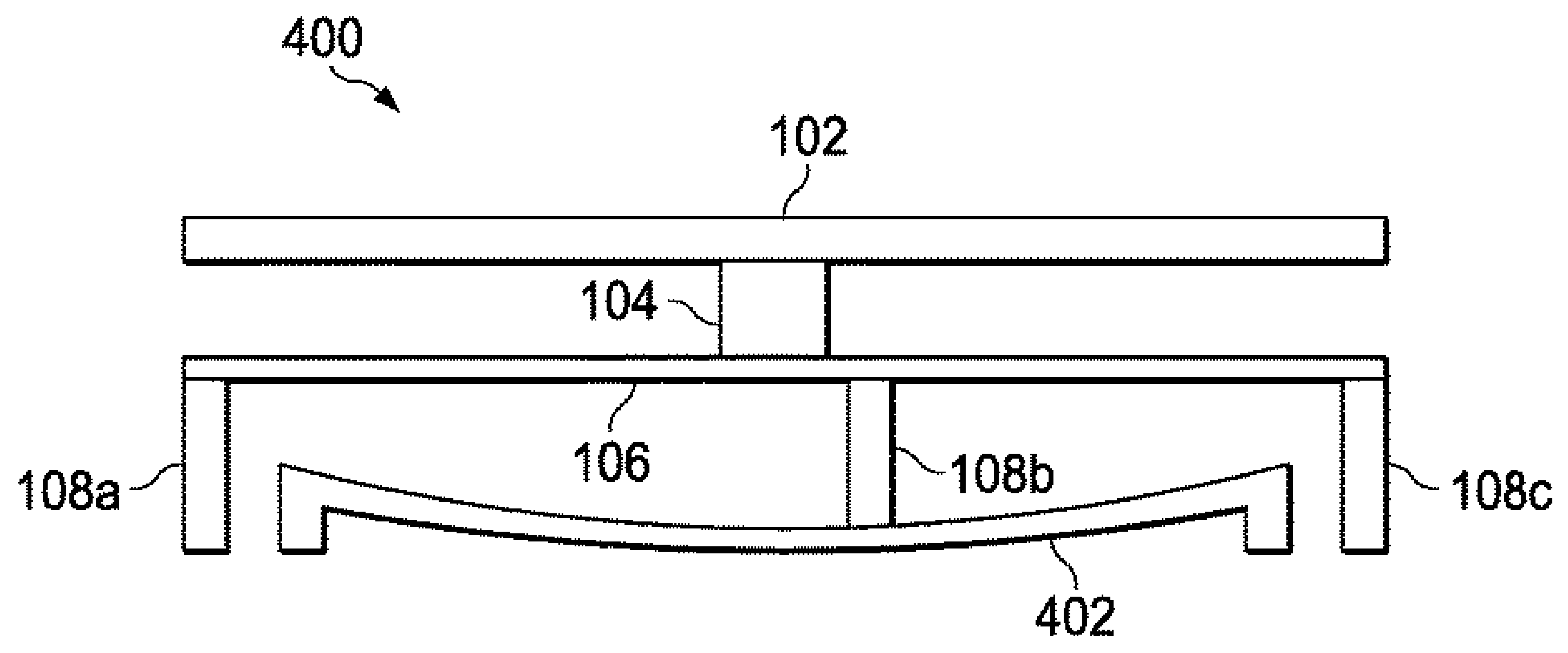
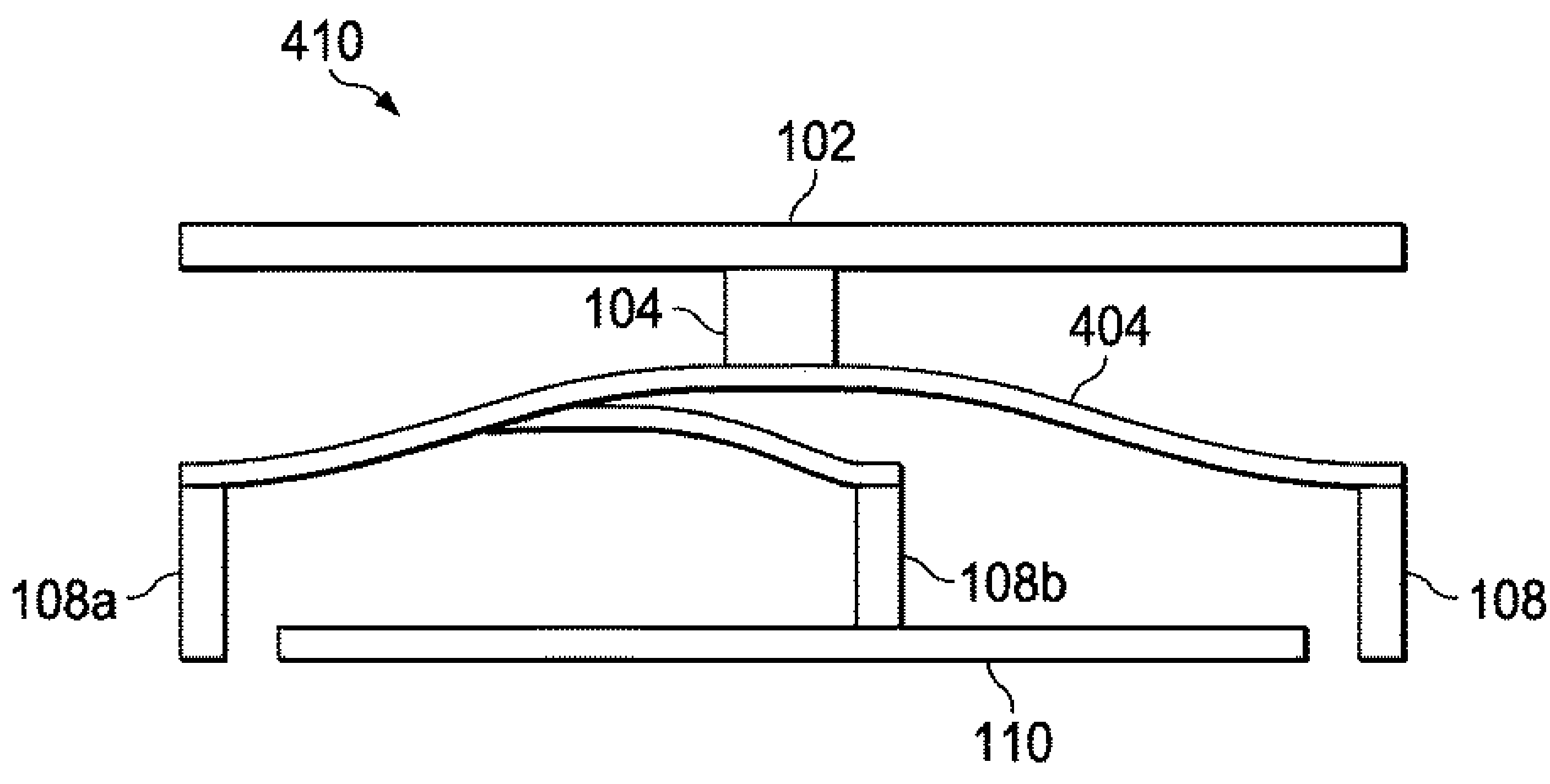
(57) **ABSTRACT**

In methods and apparatus for increasing efficiency and optical bandwidth of a microelectromechanical system piston-mode spatial light modulator, an example apparatus includes: an electrode with spring legs; a base electrode; a mirror displacement determiner to determine a periodic signal corresponding to a displacement distance of the electrode beyond an instability point of the electrode; and a voltage source to output a periodic voltage to the base electrode in response to the periodic signal. The periodic voltage causes the spring legs to vary displacement of the electrode with respect to the base electrode according to the periodic voltage. The displacement includes distances beyond the instability point.

18 Claims, 9 Drawing Sheets





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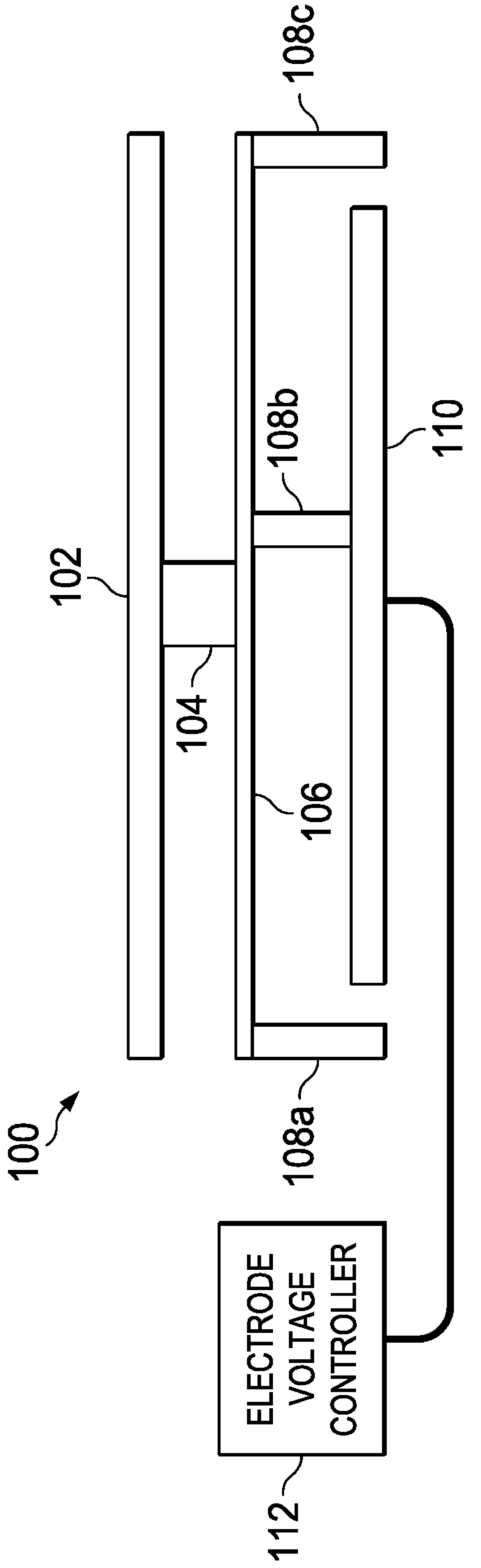
100
102
104
106
108a
108b
108c
110
112
ELECTRODE VOLTAGE CONTROLLER

FIG. 1A

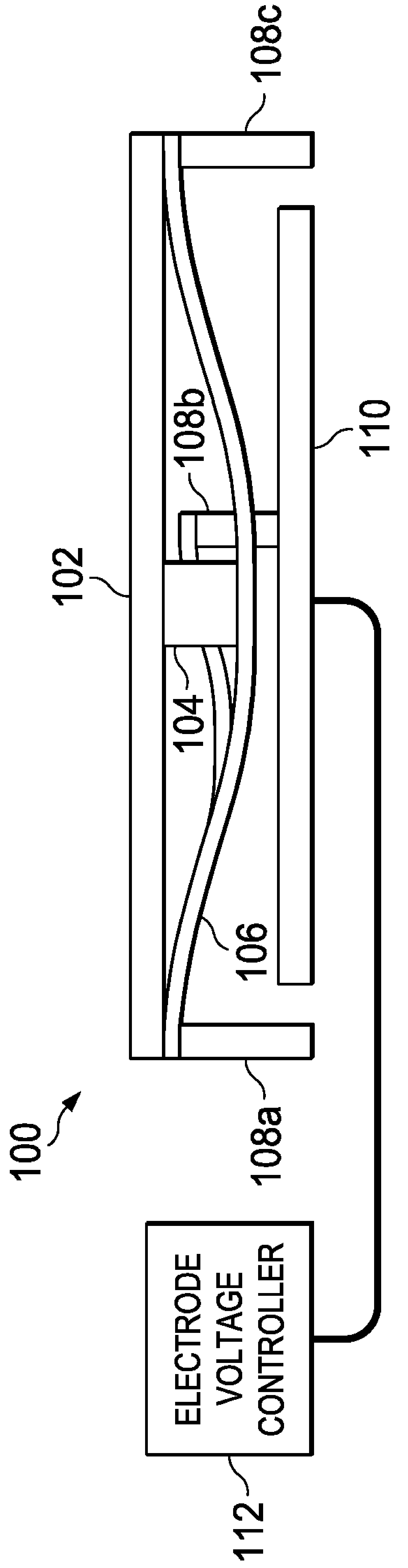
100
102
104
106
108a
108b
108c
110
112
ELECTRODE VOLTAGE CONTROLLER

FIG. 1B

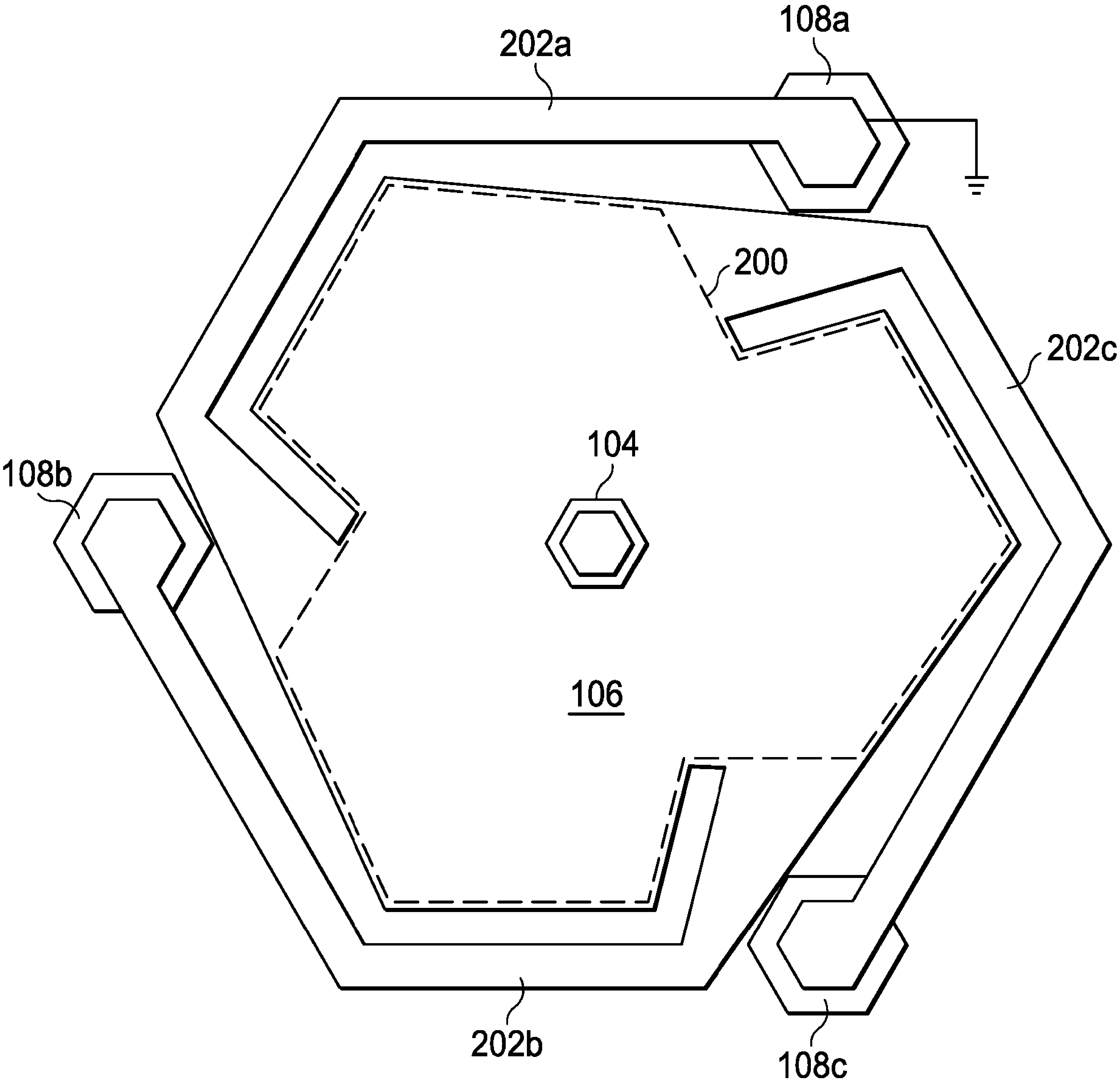

FIG. 2

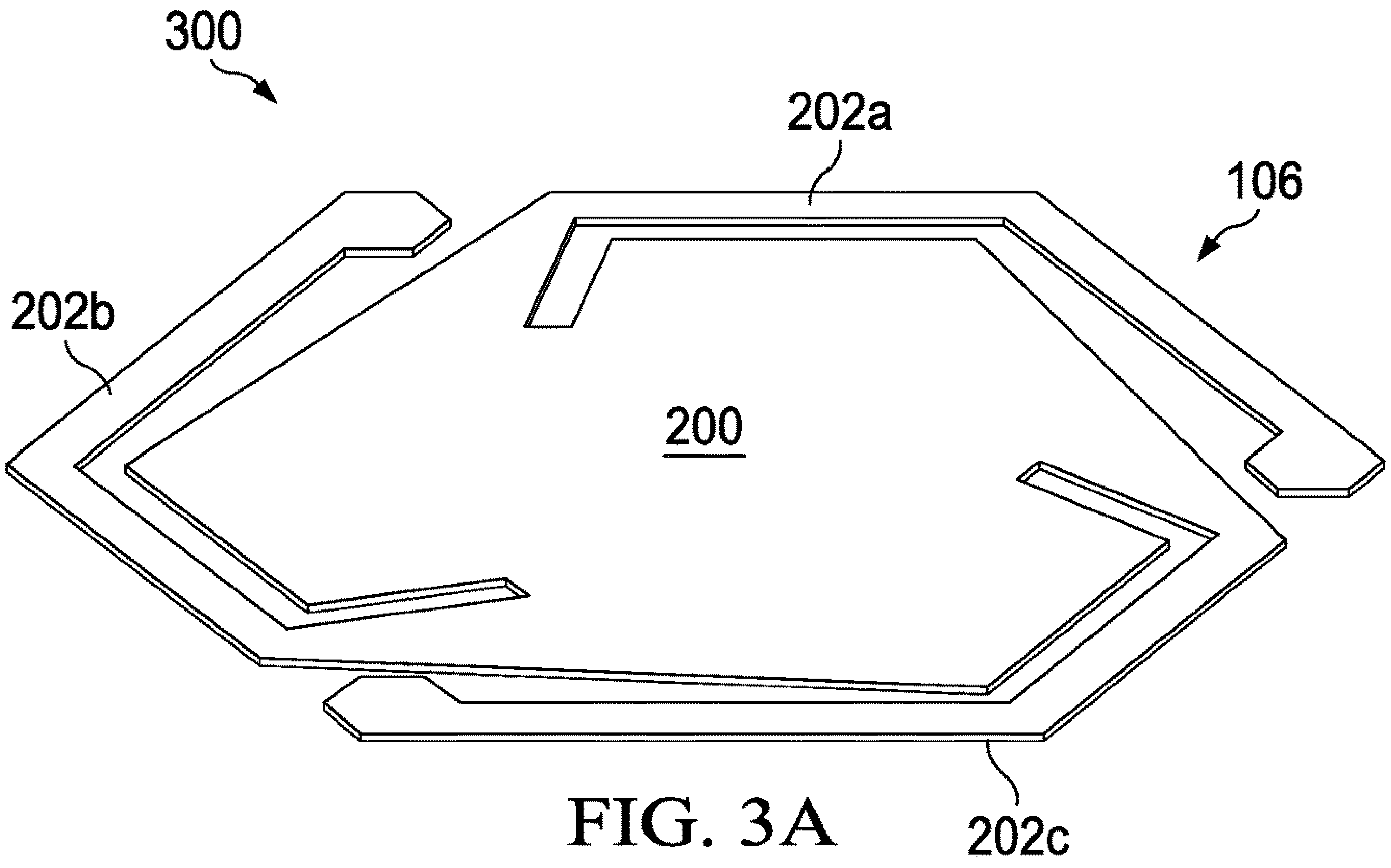

FIG. 3A

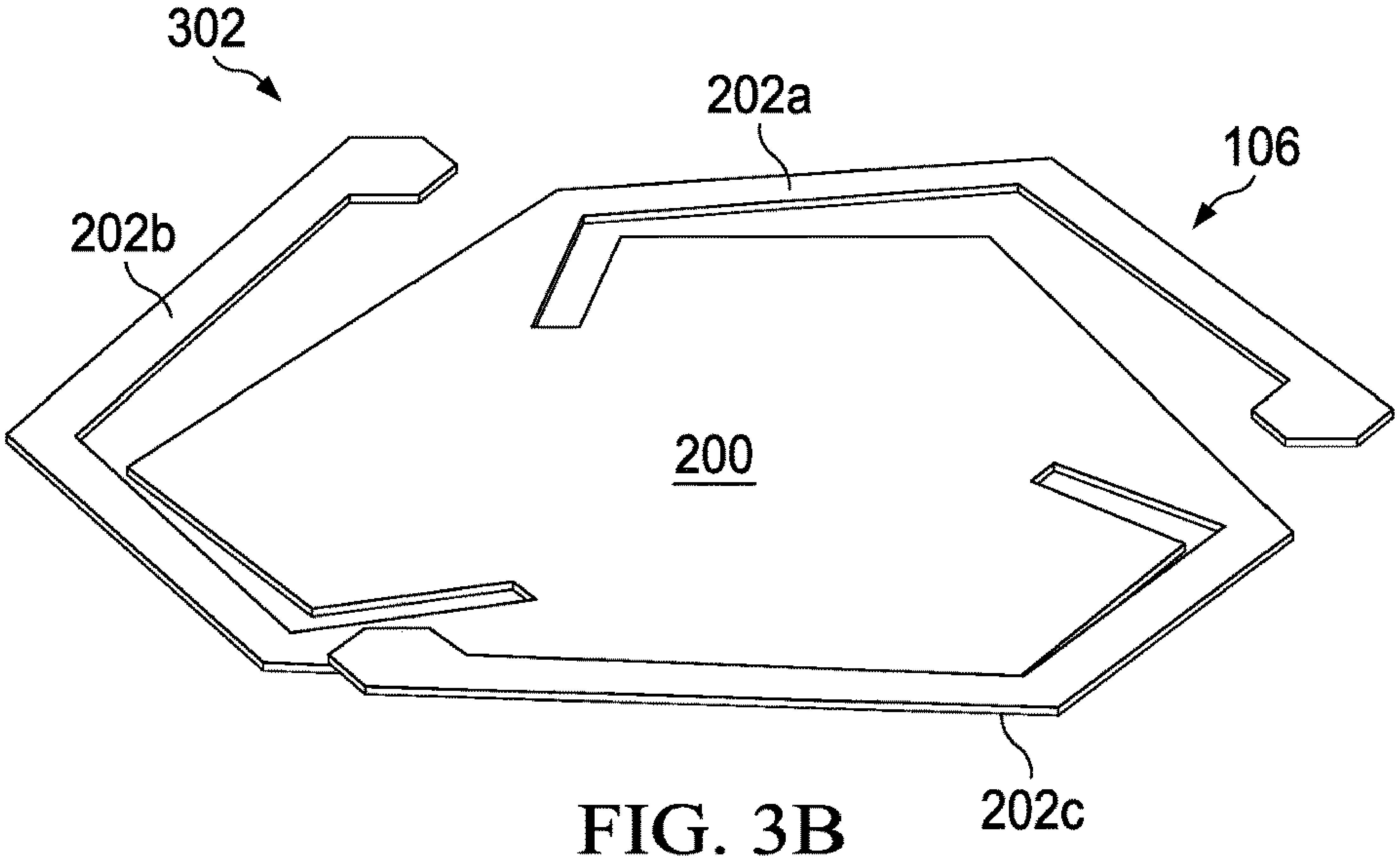

FIG. 3B

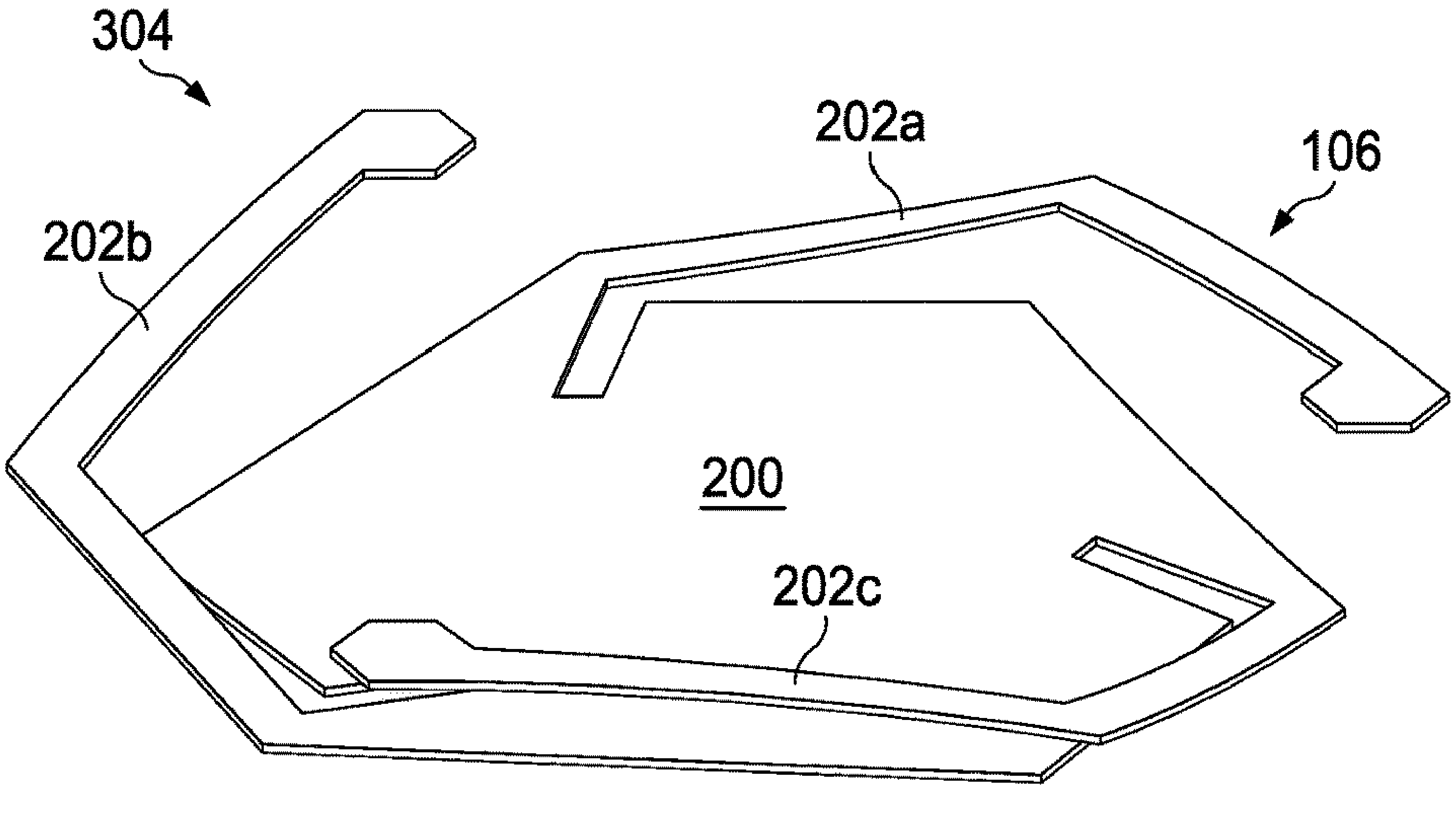

FIG. 3C

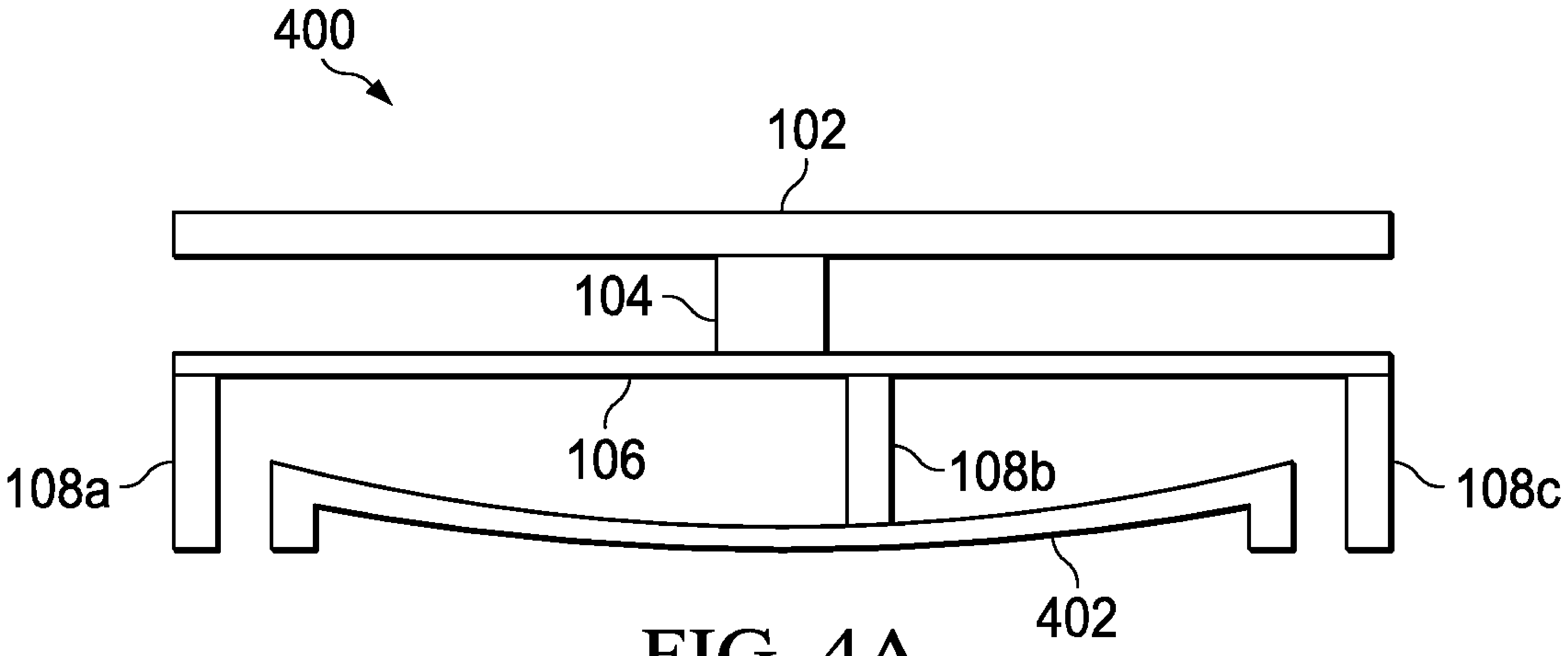

FIG. 4A

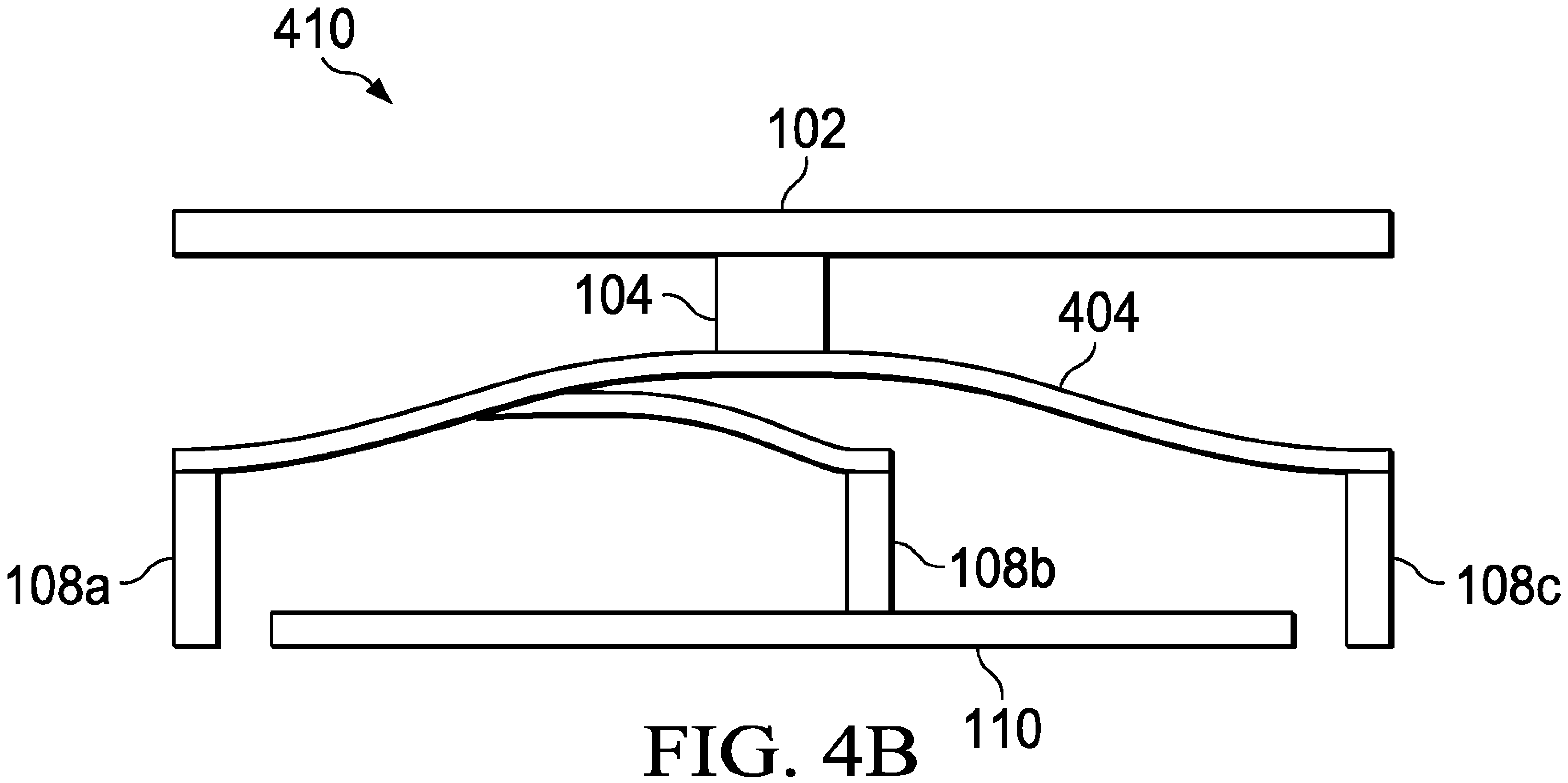

FIG. 4B

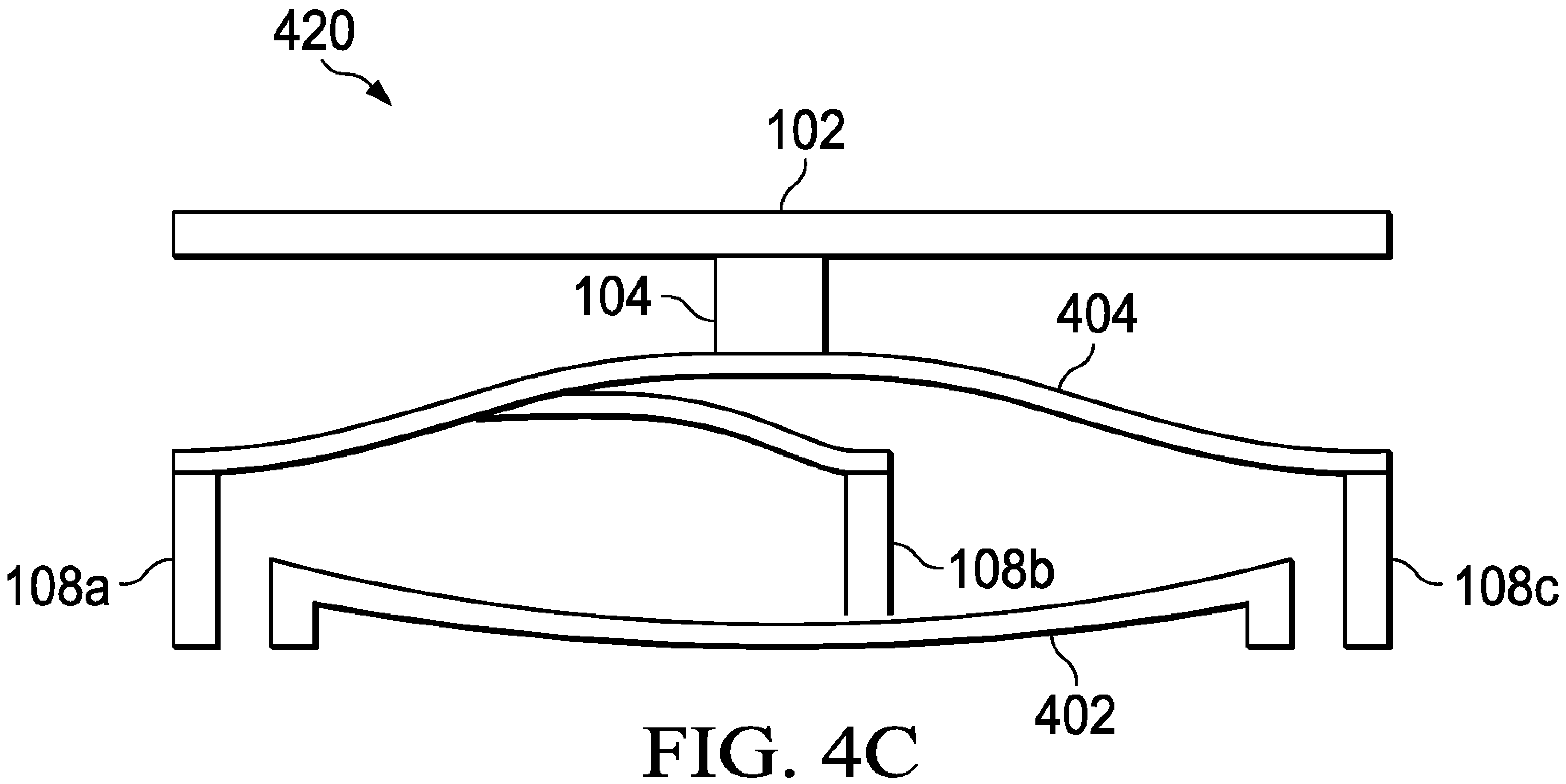

FIG. 4C

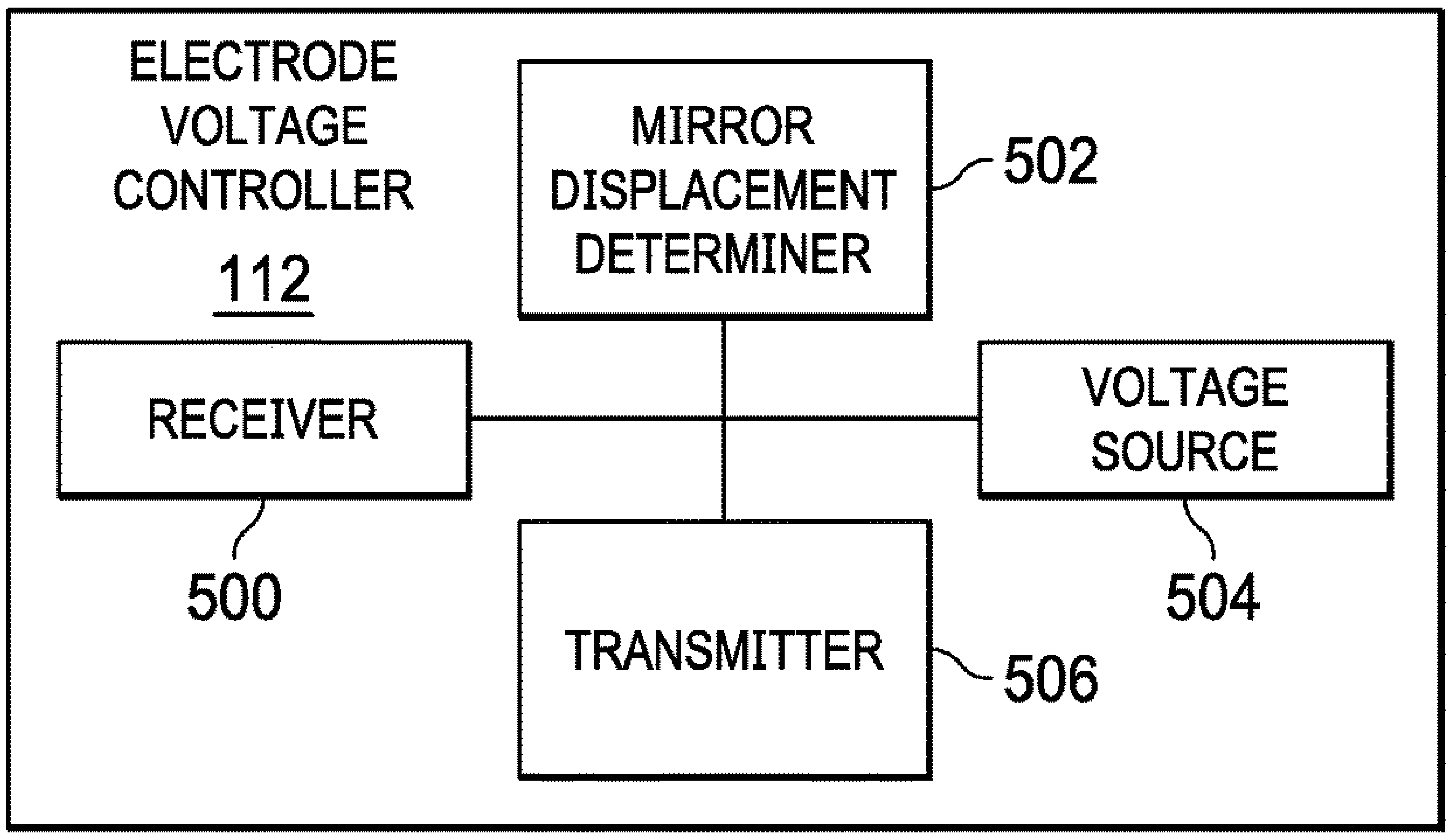
ELECTRODE VOLTAGE CONTROLLER
112
MIRROR DISPLACEMENT DETERMINER
502
RECEIVER
VOLTAGE SOURCE
500
504
TRANSMITTER
506

FIG. 5

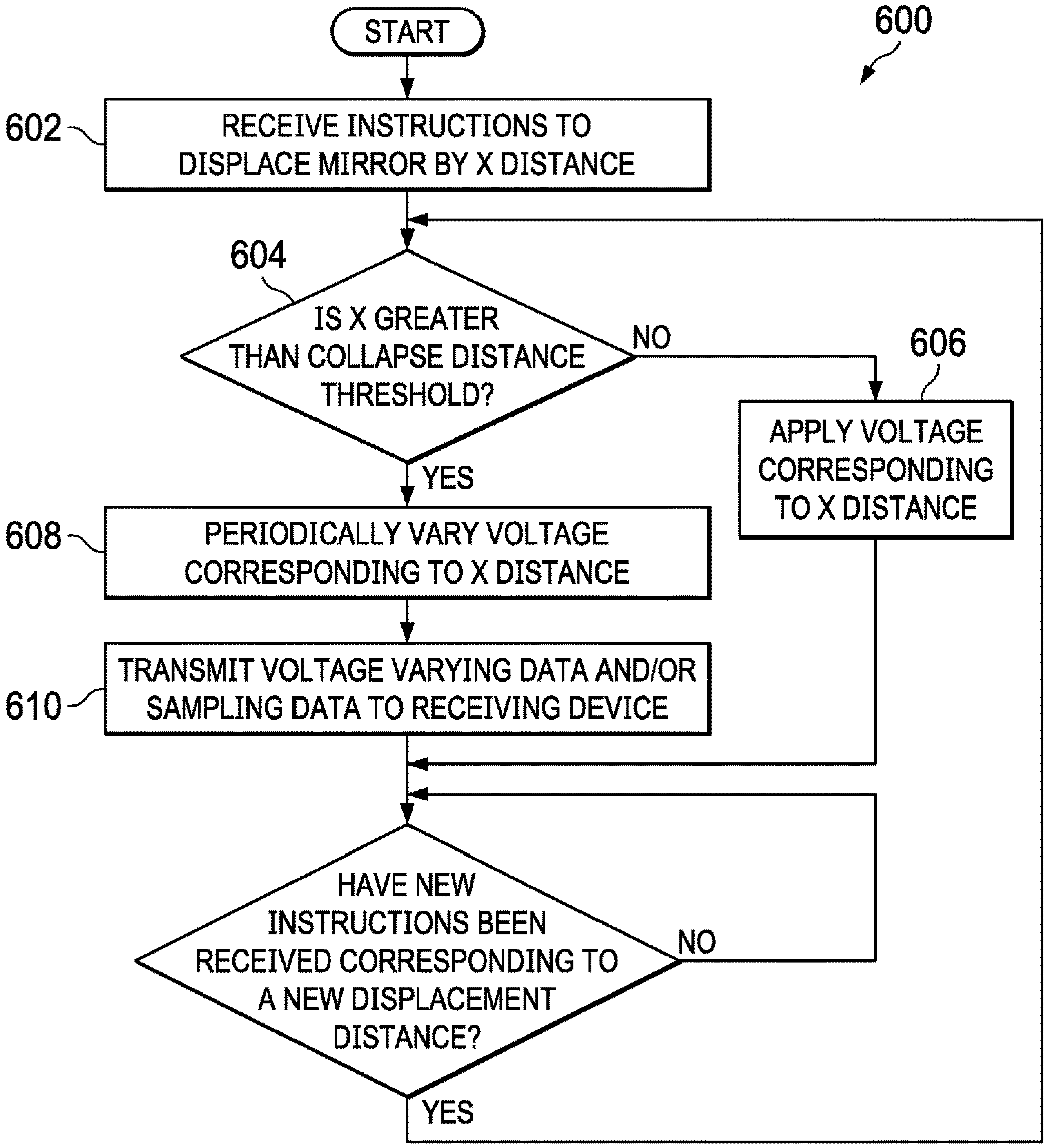
600
START
602
RECEIVE INSTRUCTIONS TO DISPLACE MIRROR BY X DISTANCE
604
IS X GREATER THAN COLLAPSE DISTANCE THRESHOLD?
NO
606
APPLY VOLTAGE CORRESPONDING TO X DISTANCE
YES
608
PERIODICALLY VARY VOLTAGE CORRESPONDING TO X DISTANCE
610
TRANSMIT VOLTAGE VARYING DATA AND/OR SAMPLING DATA TO RECEIVING DEVICE
HAVE NEW INSTRUCTIONS BEEN RECEIVED CORRESPONDING TO A NEW DISPLACEMENT DISTANCE?
NO
YES

FIG. 6

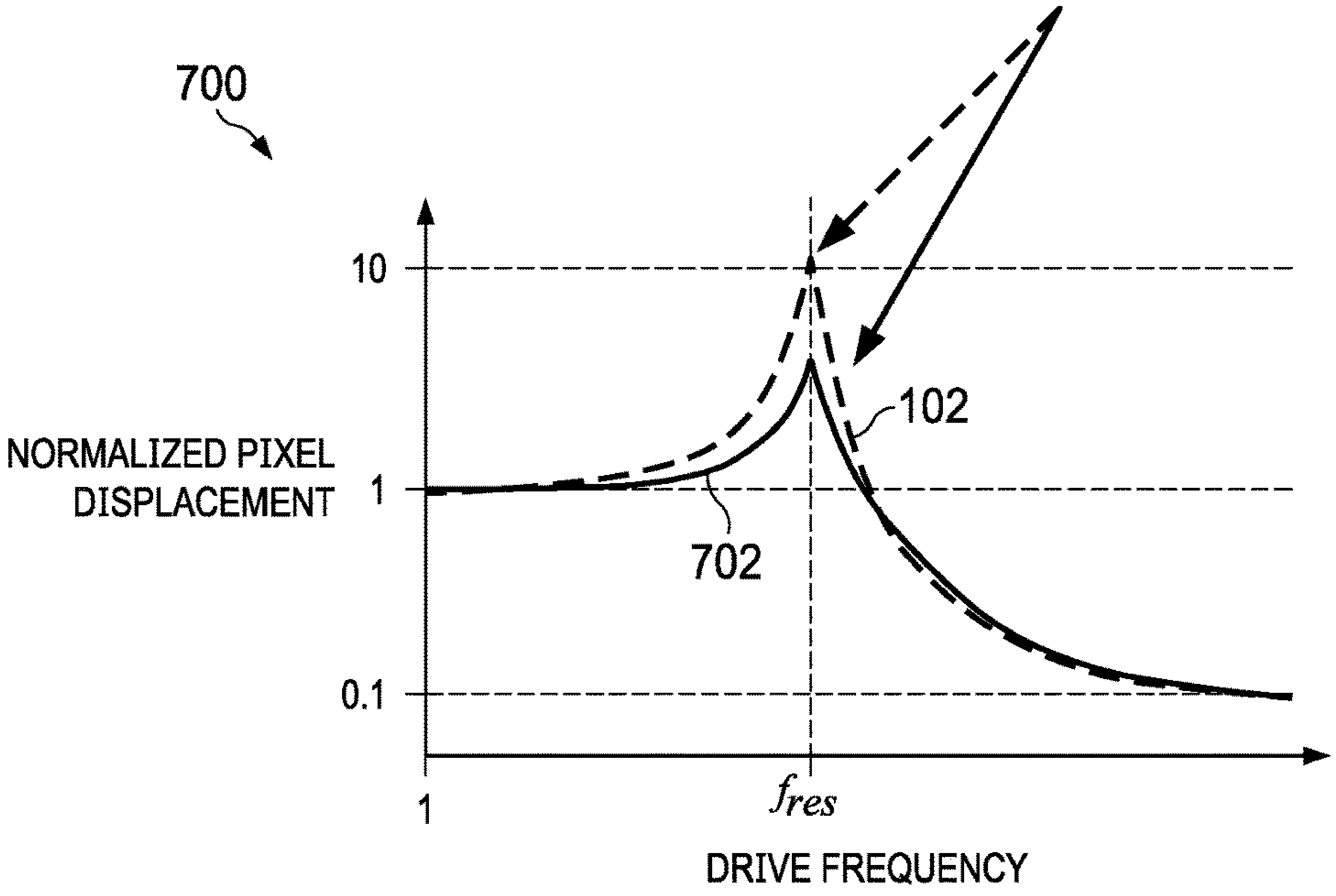
700
10
1
0.1
NORMALIZED PIXEL DISPLACEMENT
102
702
1
fres
DRIVE FREQUENCY

FIG. 7

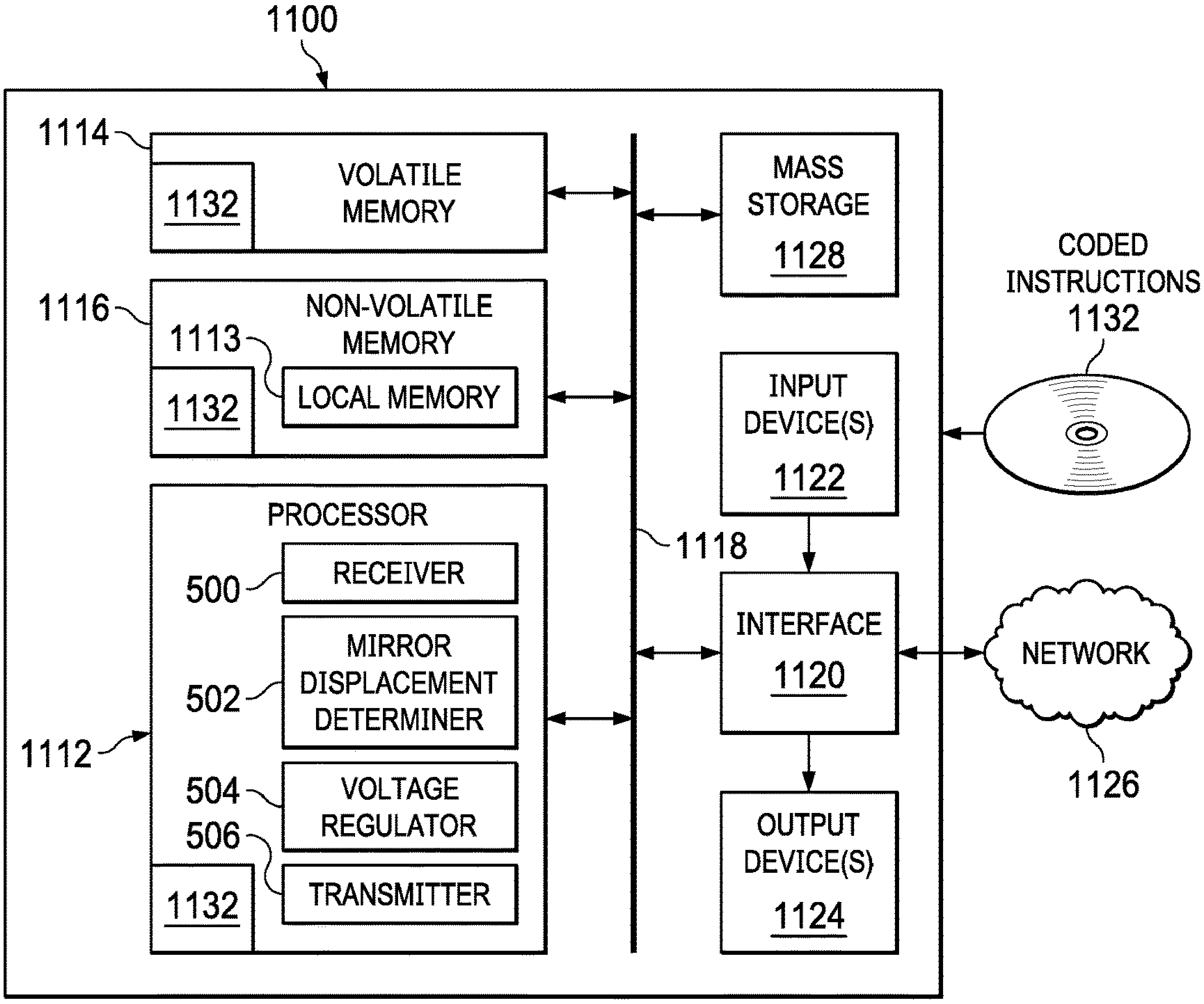
1100
1114
1132
VOLATILE MEMORY
1116
NON-VOLATILE MEMORY
1113
1132
LOCAL MEMORY
PROCESSOR
500
RECEIVER
502
MIRROR DISPLACEMENT DETERMINER
1112
504
VOLTAGE REGULATOR
506
TRANSMITTER
1132
1118
MASS STORAGE
1128
INPUT DEVICE(S)
1122
INTERFACE
1120
OUTPUT DEVICE(S)
1124
CODED INSTRUCTIONS
1132
NETWORK
1126

FIG. 11

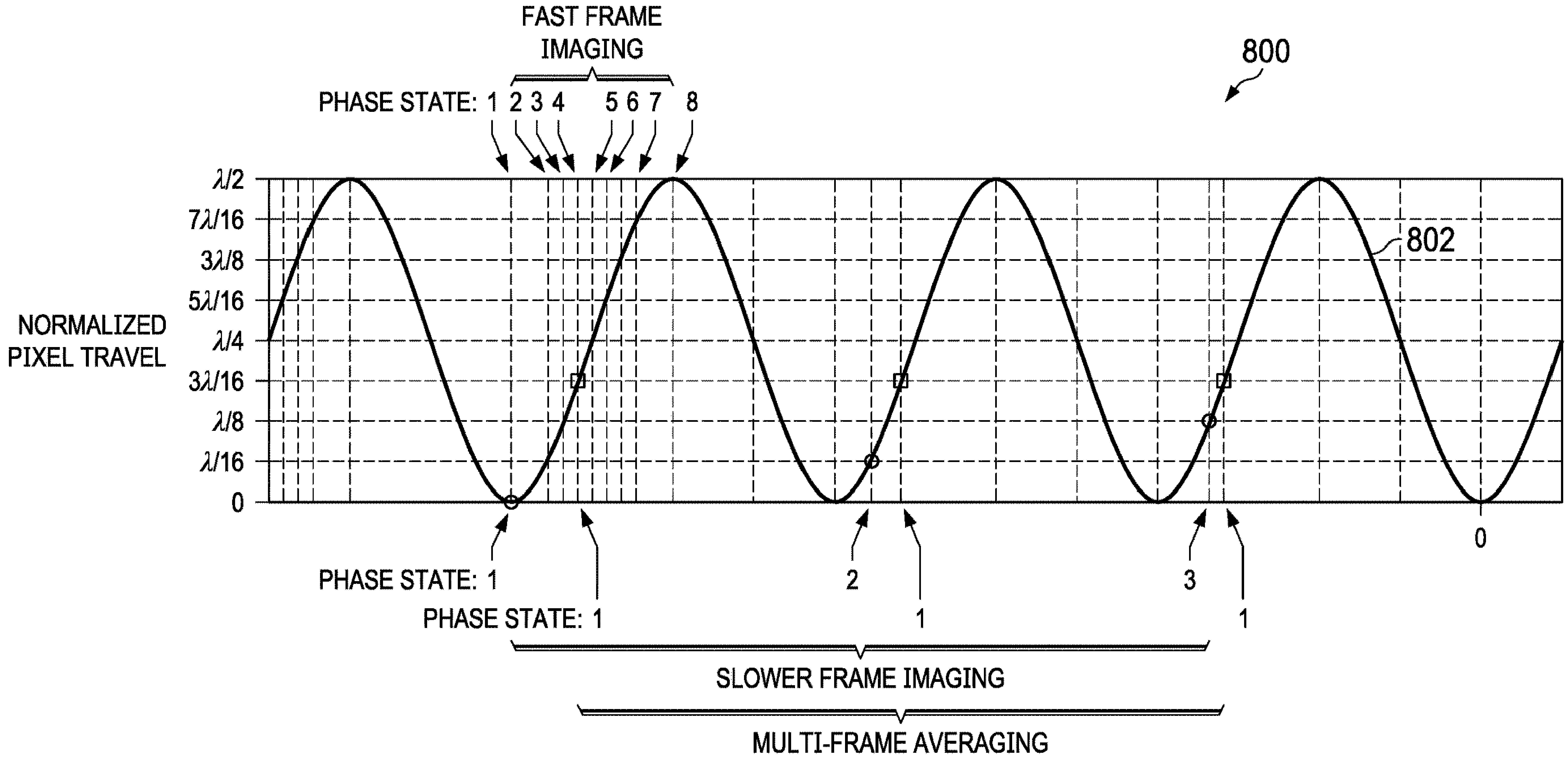
800
FAST FRAME
IMAGING
PHASE STATE: 1 2 3 4 5 6 7 8
λ/2
7λ/16
3λ/8
5λ/16
λ/4
3λ/16
λ/8
λ/16
0
NORMALIZED
PIXEL TRAVEL
802
0
PHASE STATE: 1
2
3
PHASE STATE: 1
1
1
SLOWER FRAME IMAGING
MULTI-FRAME AVERAGING

FIG. 8

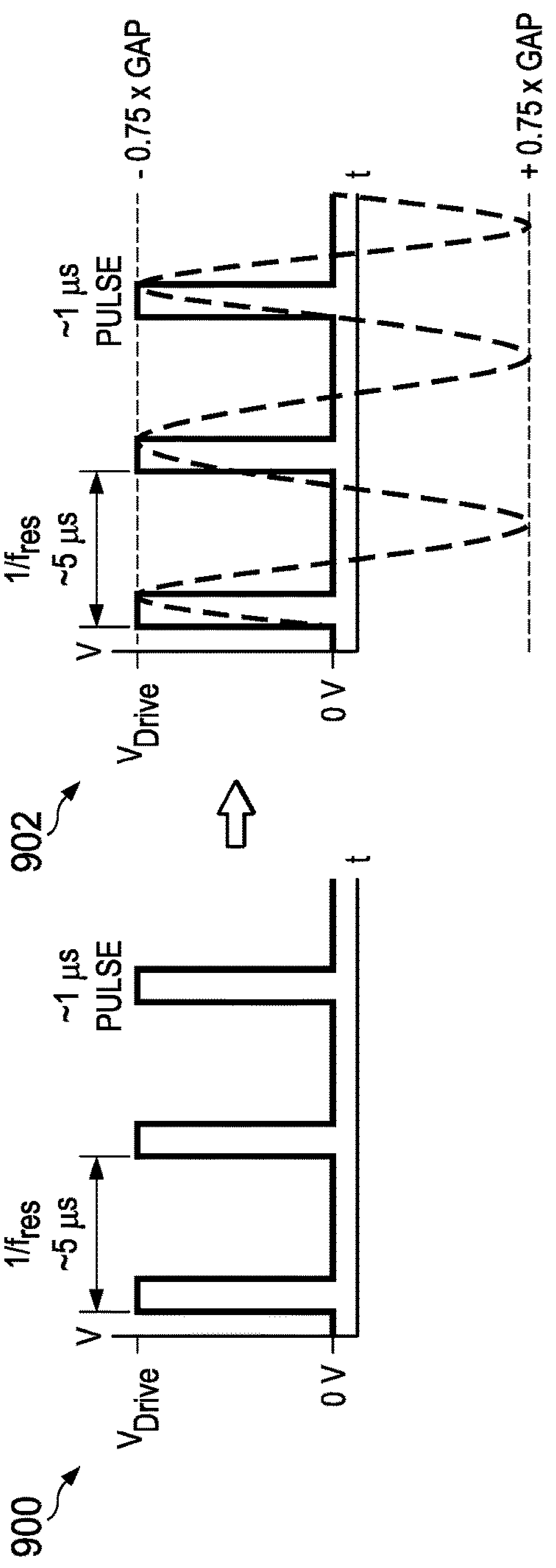
900
V_{Drive}
0 V
V
$1/f_{res}$
~5 µs
~1 µs
PULSE
t
902
- 0.75 x GAP
+ 0.75 x GAP

FIG. 9A

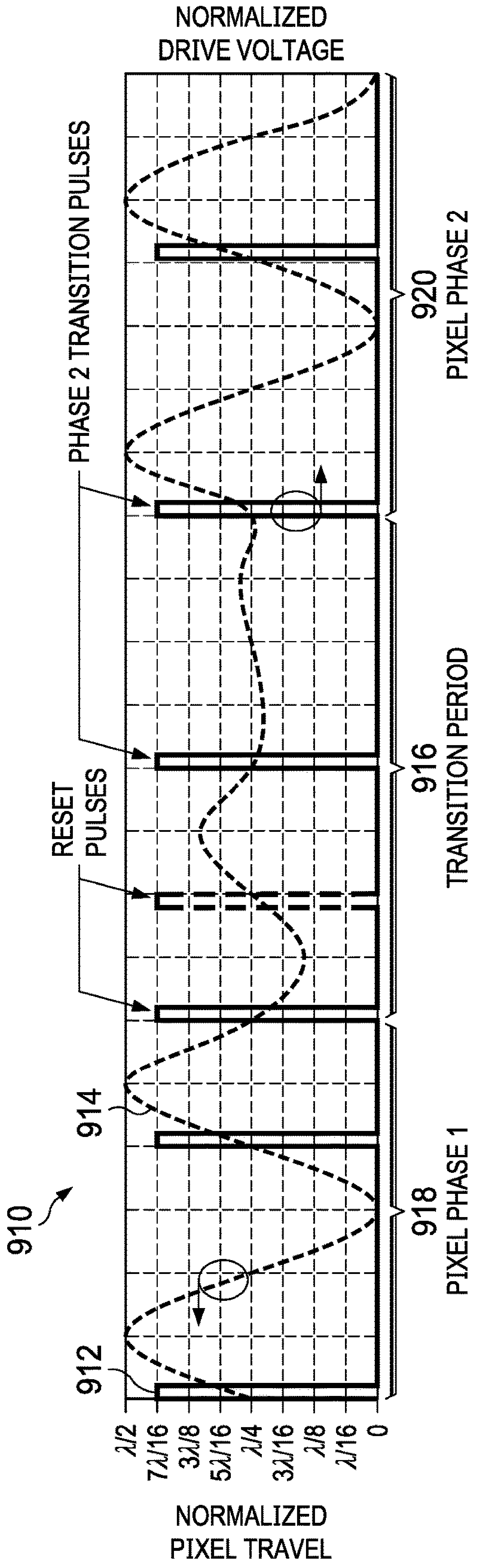
910
NORMALIZED
DRIVE VOLTAGE
NORMALIZED
PIXEL TRAVEL
λ/2
7λ/16
3λ/8
5λ/16
λ/4
3λ/16
λ/8
λ/16
0
912
914
RESET
PULSES
PHASE 2 TRANSITION PULSES
918
PIXEL PHASE 1
916
TRANSITION PERIOD
920
PIXEL PHASE 2

FIG. 9B

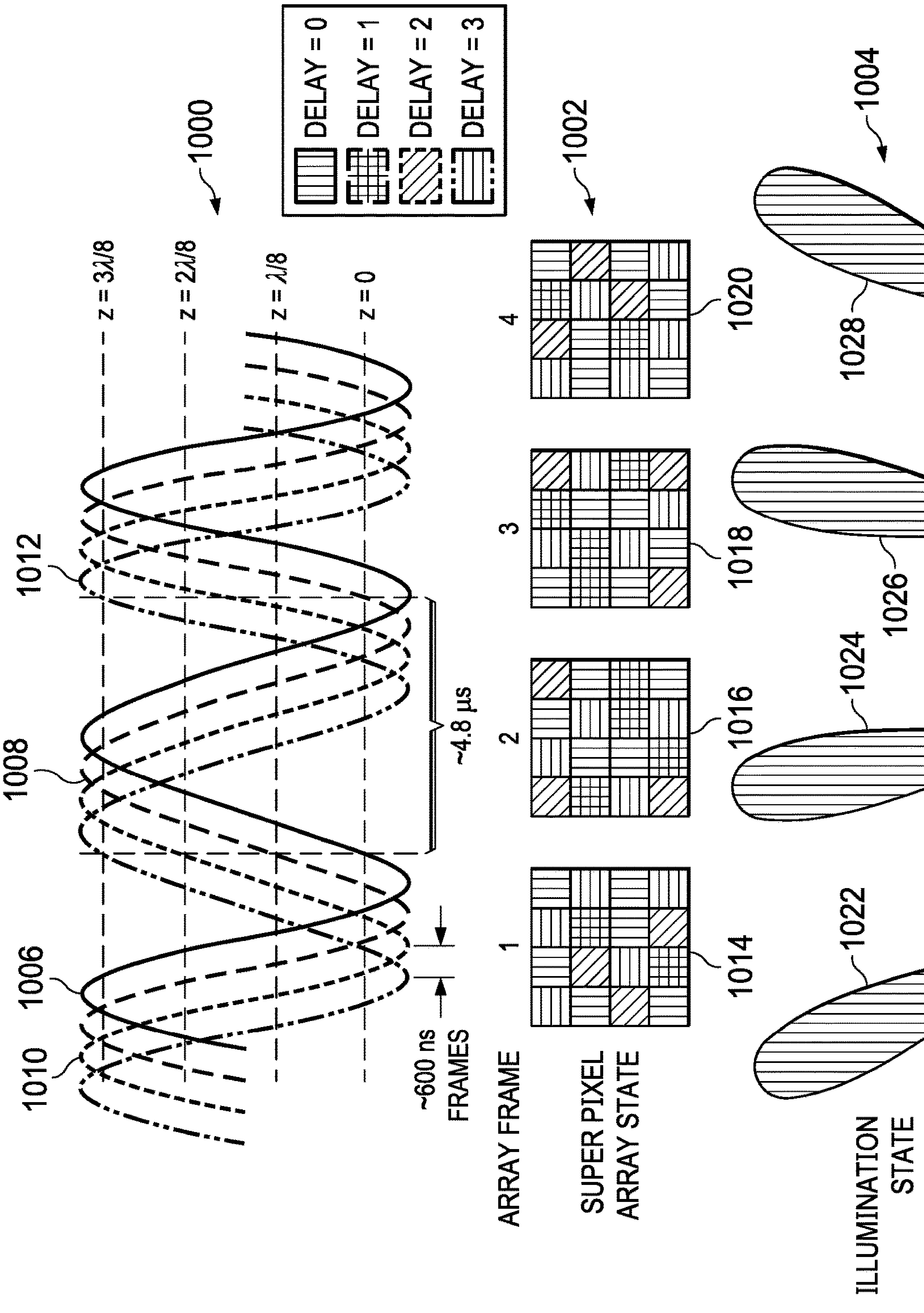
1000
1010
1006
1008
1012
z = 3λ/8
z = 2λ/8
z = λ/8
z = 0
~600 ns
FRAMES
~4.8 µs
DELAY = 0
DELAY = 1
DELAY = 2
DELAY = 3
ARRAY FRAME
1
2
3
4
SUPER PIXEL
ARRAY STATE
1002
1014
1016
1018
1020
ILLUMINATION
STATE
1004
1022
1024
1026
1028

FIG. 10

METHODS AND APPARATUS FOR INCREASING EFFICIENCY AND OPTICAL BANDWIDTH OF A MICROELECTROMECHANICAL SYSTEM PISTON-MODE SPATIAL LIGHT MODULATOR

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is related to co-owned co-pending U.S. patent application Ser. No. 15/836,536, filed Dec. 8, 2017.

TECHNICAL FIELD

This relates generally to microelectromechanical systems, and more particularly to methods and apparatus for increasing efficiency and optical bandwidth of a microelectromechanical system piston-mode spatial light modulator.

BACKGROUND

Spatial light modulators (SLMs) spatially vary modulation of a beam of light. The SLMs operate pixels, each including a respective mirror that moves to vary an intensity and/or phase of the beam of light. In some examples, microelectromechanical system (MEMS) SLMs vary positions of (e.g., move) the mirrors to change the intensity and/or phase of the beam of light. Such MEMS include a base electrode and a spring electrode coupled to the mirror. When a voltage differential is created between the base electrode (coupled to a base of a pixel) and the spring electrode, the spring electrode moves toward the base electrode, thereby moving the mirror to a different position. MEMS SLMs are used in a variety of ways, such as in projectors, high dynamic range cinema, light detection and ranging systems, high volume optical switching (e.g., in telecom or server farms), microscopy/spectroscopy/adaptive optics (e.g., in astronomy, ophthalmology, machine vision), and holographic displays.

SUMMARY

In described examples of apparatus to increase efficiency and optical bandwidth of a microelectromechanical system piston-mode spatial light modulator, the apparatus includes an electrode with spring legs. The apparatus further includes a base electrode. The apparatus further includes a mirror displacement determiner to determine a periodic signal corresponding to a displacement distance of the electrode beyond an instability point of the electrode. The apparatus further includes a voltage source to output a periodic voltage to the base electrode in response to the periodic signal, the periodic voltage to cause the spring legs to vary displacement of the electrode with respect to the base electrode according to the periodic voltage, the displacement including distances beyond the instability point.

In described examples of a method to increase efficiency and optical bandwidth of a microelectromechanical system piston-mode spatial light modulator, the method includes determining a periodic signal corresponding to a displacement distance of an electrode of a pixel beyond an instability point of the electrode. The method further includes outputting a periodic voltage to a base electrode in response to the periodic signal, the periodic voltage causing spring legs of the electrode to vary displacement of the electrode with respect to the base electrode according to the periodic voltage, the displacement including distances beyond the instability point.

In described examples of apparatus to increase efficiency and optical bandwidth of a microelectromechanical system piston-mode spatial light modulator, the apparatus includes a mirror. The apparatus further includes an electrode attached to the mirror. The electrode includes a rigid body and three spring legs coupled to the rigid body to displace the rigid body in response to an electrostatic force applied to the electrode

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. **1**A and **1**B are side views of an example MEMS SLM pixel in two different positions.

FIG. **2** is a plan view of an example spring structure of the pixel of FIGS. **1**A and **1**B.

FIGS. **3**A-**3**C are perspective views of three example displacements of the spring structure of FIGS. **1**A, **1**B and **2**.

FIGS. **4**A-**4**C are side views of three example alternative pixel structures of a MEMS SLM.

FIG. **5** is a block diagram of an example electrode voltage controller of FIGS. **1**A and **1**B.

FIG. **6** is a flowchart representative of example machine readable instructions that are executable to implement the electrode voltage controller of FIGS. **1**A and **1**B to move the position of the spring structures of FIGS. **1**A through **4**C.

FIG. **7** is an example graph of an increased travel range generated by a harmonic resonant excitation waveform.

FIG. **8** is an example graph of a sampling of light reflected off an example mirror of FIGS. **1**A and **1**B.

FIGS. **9**A and **9**B are example graphs of periodic signals that may be output by the electrode voltage controller of FIGS. **1**A, **1**B and **5** to cause the mirror of FIGS. **1**A and **1**B to periodically vary beyond an instability point without collapsing.

FIG. **10** illustrates example phase shifted mirror displacements to generate example pixel array frames corresponding to example illumination states.

FIG. **11** is a block diagram of a processor platform to execute the machine readable instructions of FIG. **6** to control the electrode voltage controller of FIGS. **1**A and **1**B.

DETAILED DESCRIPTION

The drawings are not necessarily drawn to scale. In the drawings, like parts are referenced by like reference numbers.

SLMs spatially vary modulation of a beam of light, by reflecting it to control properties (e.g., intensity and/or phase) of the reflected beam. To modulate the beam of light, SLM pixels include adjustable (movable, displaceable) mirrors to change the reflected beam's properties. In some examples, SLMs include MEMS to move the mirrors in response to a combination of an electrostatic force and a spring force.

FIGS. **1**A and **1**B are side views of two positions of an example pixel **100** of a MEMS SLM. FIGS. **1**A and **1**B show an example mirror **102**, an example mirror attachment **104** (e.g., a mirror via), an example spring **106** (e.g., herein referred to as "spring," "spring structure" or "spring electrode") (e.g., a first electrode), example spring attachments **108***a-c* (e.g., a spring via), an example base electrode **110** (e.g., a second electrode), and an example electrode voltage controller **112**.

The mirror **102** reflects a beam of light in one or more directions, according to a position of the mirror. For example, the mirror **102** is extended in a first position in FIG. **1**A to reflect light, and the mirror **102** is retracted to a second position in FIG. **1**B to reflect light. The mirror **102** reflects light corresponding to a pure phase contrast device with a continuous phase range. In this manner, an array of mirrors may be displaced in different positions to create different interference patterns (e.g., corresponding to different intensities).

The spring **106** is an electrode including spring legs and a rigid body. The spring structure **106** is coupled to the mirror **102** via the mirror attachment **104**, thereby providing additional rigidity to the rigid body. The spring legs of the spring structure **106** correspond to a mechanical spring constant that, when stretched, applies a mechanical force in the opposite direction of the stretching. The spring legs are attached to the spring attachments **108***a-c*, which may be grounded. In this manner, when an electrostatic force is applied to the spring structure **106** in a downward motion, the spring legs extend toward the base electrode **110**, causing the rigid body of the spring structure **106** to lower, thereby causing the mirror **102** to move from the position of FIG. **1**A toward the position of FIG. **1**B. Although the spring structure **106** may be any shape, a hexagon-shaped spring structure increases an area-to-perimeter ratio of the rigid body, so the voltage applied to the base electrode **110** may be significantly lower than conventional pixels without reducing the pixel's quality (e.g., corresponding to a total distance of the mirror displacement).

In some examples, a length of the spring attachments **108***a-c* is longer than a length of the mirror attachment **104**. In this manner, even if the mirror **102** is fully displaced by the electrostatic force, the spring structure **106** will not directly contact the base electrode **110** (e.g., will not cause an electrical short). In some examples, the mirror **102**, the mirror attachment **104**, the spring structure **106**, and/or the spring attachments **108***a-c* are covered by a similar material. In this manner, a zero-voltage potential exists between the mirror **102**, the mirror attachment **104**, the spring structure **106**, and/or the spring attachments **108***a-c*.

In operation, the base electrode **110** receives a voltage from the electrode voltage controller **112**. The voltage on the base electrode **110** generates an electrostatic force that, when stronger than the spring constant of the spring structure **106**, causes the spring structure **106** to move toward the base electrode **110**. A displacement of the spring structure **106** increases as more voltage is applied on the base electrode **110**, and/or as more area of the voltage is applied by the base electrode **110**. In some examples, the base electrode **110** is an analog-type electrode, in which the voltage is equally spread throughout the base electrode **110**. Accordingly, the electrode voltage controller **112** outputs an analog voltage in order to move the spring structure **106** and the mirror **102** to different positions (e.g., each voltage level corresponding to a different position). In some examples, the base electrode **110** is a digital-type electrode, in which the voltage is applied to different areas (e.g., bits) of the base electrode **110**. For example, the base electrode **110** may include three bits (bit_**0**, bit_**1**, and bit_**2**), for linear bit spacing, so the areas increase binarily (e.g. bit **0** is ½ the area of bit **1**, and bit **1** is ½ the area of bit **2**. However, this area ratio may be varied to compensate for nonlinearity of the electrostatic force, curved/sloped electrodes, and/or nonlinear springs, as further described hereinbelow. Although the example of FIGS. **1**A and **1**B corresponds to a 3-bit electrode configuration, the base electrode **110** may include any number of bits, subject to lithography and routing limitations. Accordingly: (a) if 5 V is applied to bit_**0**, then the spring structure **106** is moved to a first position; (b) if 5 V is applied to bit_**0** and bit_**1**, then the spring structure **106** is moved to a second position (lower than the first position); and (c) if 5 V is applied to bit_**0**, bit_**1** and bit_**2**, then the spring structure **106** is moved to a third position (lower than the second position).

The electrode voltage controller **112** controls the displacement of the mirror **102** by transmitting a voltage to the base electrode **110** to generate an electrostatic force between the base electrode **110** and the spring structure **106**, thereby causing the spring structure **106** (and thus the mirror **102**) to move toward the base electrode **110**. The electrode voltage controller **112** applies the voltage to correspond to a distance, according to a desired output (e.g., received from another computing device or circuit). In some examples, the electrode voltage controller **112** generates a periodic signal (e.g., a digital pulsing signal or a sinusoid) that causes the spring structure **106** (e.g., and thus the mirror **102**) to be pulled toward and away from the base electrode **110** in a periodic fashion. As described herein, periodically varying the voltage to periodically vary the displacement of the spring structure **106** allows the electrode voltage controller **112** to move the spring structure **106** beyond a d/3 threshold distance (e.g., an instability point) toward the base electrode **110** without collapsing (e.g., without causing the spring structure **106** to collapse toward the base electrode **110**). The electrode voltage controller **112**, using the periodic varying technique, is able to move the spring structure **106** to about 9/10 the distance to the base electrode **110**. Because the electrode voltage controller **112** is varying the displacement of the spring structure **106** with time, a receiving device (e.g., receiving light reflected by the mirror **102**) needs to obtain the information regarding the periodic variation to sample the received signal (e.g., the light reflected of the mirror **102**) according to a desired displacement. For example, if the electrode voltage controller **112** is varying the voltage applied by the base electrode **110** to move the spring structure **106** at a particular rate with a particular total distance (e.g., amplitude of the periodic displacement), the receiving device can sample the received signal for a desired displacement according to the known rate and distance. Although example electrode voltage controller **112** controls the pixel **100**, the electrode voltage controller **112** may control multiple pixels. For example, the electrode voltage controller **112** may be coupled to base electrodes that each operate independently, as a group, or as subgroups (e.g., a first subgroup controlled with a first voltage and a second subgroup controlled by a second voltage). The electrode voltage controller **112** is further described hereinbelow in conjunction with FIG. **5**.

FIG. **2** illustrates an example overhead view of the spring structure **106** above the base electrode **110** of the pixel **100** of FIGS. **1**A and **1**B. The overhead view of FIG. **2** includes the mirror attachment **104**, the spring structure **106**, the spring attachments **108***a-c*, and the base electrode **110** of FIGS. **1**A and **1**B. The spring structure **106** of FIG. **2** includes an example body **200** and example spring legs **202***a-c*.

As described herein, the spring structure **106** of FIG. **2** is a three-legged hexagon-shaped spring structure that increases the area-to-perimeter ratio of the rigid body thereby allowing the voltage applied to the base electrode **110** to be significantly lower than conventional pixels without reducing the quality (e.g., corresponding to the total distance that the mirror displacement) of the pixel. Alternatively, the spring structure **106** may be a different shape with a different area-to-perimeter ratio corresponding to a different voltage that may need to be applied by the base electrode **110**.

The body **200** of FIG. **2** is a rigid structure that maintains its structure when the base electrode **110** increases voltage. When the base electrode **110** increases voltage, the body **200** moves toward the base electrode **110** while maintaining its form. In this manner, the surface area exposed to the base electrode voltage is increased to increase the overall efficiency of the structure. The mirror attachment **104** attaches to the body **200**, thereby causing the mirror **102** of FIG. **2** to move with the movement of the body **200**. Also, the mirror attachment **104** provides additional rigidity to the body **200**. Although the mirror attachment **104** is attached to the spring structure **106** in the middle, the mirror attachment **104** may be attached anywhere along the body **200** and/or may include multiple mirror attachments at various locations on the body **200**. These multiple attachment points can be used to increase the stiffness of the main lower electrode body while weakening the spring legs, or vice versa. The body **200** is attached to the spring legs **202***a-c*.

The spring legs **202***a-c* of FIG. **2** are attached to the spring attachments **108***a-c* and the spring body **200**. In the illustrated example, the spring attachment **108***a-c* is grounded; thus, the spring legs **202***a-c* and the spring body **200** are also grounded. The spring legs **202***a-c* include a spring constant corresponding to a spring force to maintain the body **200** at a first position. As the electrostatic force of the base electrode **110** increases (e.g., according to a voltage differential between the grounded spring structure **106** and the biased base electrode **110** of FIGS. **1**A and **1**B), the spring legs **202***a-c* are stretched toward the base electrode **110**, thereby lowering the body **200**. The spring constant may be based on the material of the spring structure **106** and/or based on the dimensions of the spring legs **202***a-c*. For example, the spring legs **202***a-c* are long and wrapped around the hexagon structure before blending into the body **200**. Such a structure provides give that corresponds to a spring constant, while preserving the area-to-perimeter ratio of the body **200**. In the illustrated example, the spring structure **106** is one unified piece of unified material (e.g., the body **200** and the spring legs **202***a-c* are made of a same material and are integral within a same structure). However, the body **200** and the spring legs **202***a-c* may be different materials attached together (e.g., a first material to correspond to the spring constant of the spring legs **202***a-c* and a second material to correspond to the rigidity of the body **200**). The three-legged hexagon structure of FIG. **2** decreases the stiffness (e.g., the spring constant) of the spring legs **202***a-c*, while providing sufficient support for the body **200**.

FIGS. **3**A-**3**C illustrate three example displacements of the spring structure of FIGS. **1**A, **1**B and **2**. FIGS. **3**A-**3**C include the body **200** and the spring legs **202***a-c* of the spring structure **106** of FIG. **2**. FIG. **3**A illustrates an example first spring displacement **300** corresponding to a first voltage being applied to the base electrode **110** of FIGS. **1**A and **1**B. FIG. **3**B illustrates an example second spring displacement **302** corresponding to a second voltage being applied to the base electrode **110** of FIGS. **1**A and **1**B. FIG. **3**C illustrates an example third spring displacement **304** corresponding to a third voltage being applied to the base electrode **110** of FIGS. **1**A and **1**B.

In FIG. **3**A, the electrode voltage controller **112** is not applying a voltage to the base electrode **110**. Because no voltage differential exists between the spring structure **106** and the base electrode **110**, no electrostatic force exists to

pull the body **200** toward the base electrode **110**. Accordingly, FIG. **3**A illustrates the spring structure **106** with no displacement. For example, the spring legs **202***a-c* are at the same level as the spring body **200**, and no downward force is being applied.

In FIG. **3**B, the electrode voltage controller **112** is applying a first voltage to the base electrode **110** (e.g., a first analog voltage throughout the base electrode **110** or a voltage corresponding to a first area of the total area of the base electrode **110**). The first voltage applied to the base electrode **110** causes a first voltage differential between the base electrode **110** and the spring structure **106**, thereby causing an electrostatic force to drive the body **200** downward towards the base electrode **110**. The first voltage corresponds to a first electrostatic force that causes the spring legs **202***a-c* to stretch and lower the body **200** to a first position (e.g., corresponding to a 10 millimeter (mm) displacement) from the position of FIG. **3**A).

In FIG. **3**C, the electrode voltage controller **112** is applying a second voltage to the base electrode **110** (e.g., a second analog voltage higher than the first analog voltage of FIG. **3**B or the voltage of FIG. **3**B corresponding to a second area larger than the first area of the base electrode **110**). The second voltage (e.g., higher or over a wider area) applied to the base electrode **110** causes a second, higher voltage differential between the base electrode **110** and the spring structure **106**, thereby causing an electrostatic force to drive the body **200** further downward towards the base electrode **110**. The second voltage corresponds to a second electrostatic force that causes the spring legs **202***a-c* to stretch further and lower the body **200** to a second position (e.g., corresponding to a 30 millimeter (mm) displacement) from the position of FIG. **3**A).

As illustrated in FIGS. **3**A-**3**C, the stronger the voltage applied to the base electrode **110** (e.g., higher voltage or over a larger area), the further the body **200** displaces towards the base electrode **110**. As described herein, in each position of the body **200**, the body **200** remains rigid, while the spring legs **202***a-c* stretch in response to the electrostatic force.

FIGS. **4**A-**4**C illustrate three example alternative pixel structures of a MEMS SLM. The examples of FIGS. **4**A-**4**C include the mirror **102**, the mirror attachment **104**, the spring structure **106**, the spring attachment **108***a-c*, and the base electrode **110** of FIGS. **1**A and **1**B. The examples of FIGS. **4**A-**4**C further include an example non-uniform base electrode **402** and an example non-uniform spring structure **404** in a first example pixel structure **400**, a second example pixel structure **410**, and/or a third example pixel structure **420**.

The first example pixel structure **400** of FIG. **4**A includes the non-uniform base electrode **402**. The non-uniform base electrode **402** has a structure that is gray scale slopped rather than flat. The non-uniform base electrode **402** may be curved, bowled, slanted, sloped, and/or any other structure other than a flat structure. For example, the non-uniform base electrode **402** may be curved away from each other (e.g., to progressively increase the distance d over position). For example, in such curved structures, the distance d between the base electrode **402** and the spring electrode **106** increases as the position along the actuating structure increase from the support structure. Adjusting (e.g., curving) the base electrode **402** changes the electrostatic force from uniform, linear forces to non-uniform, non-linear forces. In this manner, when the spring structure **106** approaches the non-uniform base electrode **402**, more force will exist near the spring attachment **108***a-c*, and more restoring force will exist from the spring structure **106** (e.g., the larger the displacement, the larger the resistance of the spring structure **106**). By progressively moving the non-uniform base electrode **402** away from the weakest part of the spring structure **106**, overall pixel travel is increased, such as from the d/3 threshold of instability to a 2d/3 threshold of instability (e.g. twice the travel of conventional MEMS pixel travel), without collapsing (e.g., without any risk of collapse).

The first example pixel structure **410** of FIG. **4**B includes the non-uniform spring structure **404**. The non-uniform spring structure **404** has a structure that is gray scale sloped rather than flat. The non-uniform spring structure **404** may be curved, bowled, slanted, sloped, and/or any other structure other than a flat structure. For example, the non-uniform spring structure **404** may be curved away from each other (e.g., to progressively increase the distance d over position). For example, in such curved structures, the distance d between the base electrode **110** and the spring electrode **404** increases as the position along the actuating structure increase from the support structure. Adjusting (e.g., curving) the spring structure **404** changes the electrostatic force from uniform, linear forces to non-uniform, non-linear forces. In this manner, when the spring structure **404** approaches the base electrode **110**, more force will exist near the spring attachment **108***a-c*, and more restoring force will exist from the spring structure **404** (e.g., the larger the displacement, the larger the resistance of the spring structure **404**). By progressively moving the weakest part of the non-uniform spring structure **404** away from the base electrode **110**, overall pixel travel is increased, such as from the d/3 threshold of instability to a 2d/3 threshold of instability (e.g. twice the travel of conventional MEMS pixel travel), without collapsing. The third example pixel structure **420** of FIG. **4**C includes the non-uniform base electrode **402** and the non-uniform spring structure **404** of FIGS. **4**A and **4**B. Like the pixel structures **400** and **410**, the pixel structure **420** corresponds to overall pixel travel increase, such as from the d/3 threshold of instability to a 2d/3 threshold of instability (e.g. twice the travel of conventional MEMS pixel travel), without collapsing.

Accordingly, MEMS may apply electrostatic force to move the mirror **102** of an SLM pixel **100**, **400**, **410**, **420**. For example, the MEMS pixel **100**, **400**, **410**, **420** includes the first electrode **106**, **404** coupled to the mirror **102**. The first electrode **106**, **404** is also anchored to the attachment **104**, which is a distance d away from a second electrode **110**, **402** (e.g., above the second electrode **110**, **402** in a vertical construction). The first electrode **106**, **404** includes one or more springs to maintain a position of the first electrode **106**, **404** (e.g., the distance d away from the second electrode **110**, **402**), but allowing the first electrode **106**, **404** to move in and out (e.g., up and down in a vertical construction) if a second force overcomes the spring force. The first electrode **106**, **404** is grounded, and the second electrode **110**, **402** is coupled to a voltage regulator **504**. The voltage regulator **504** applies a bias voltage to the second electrode **110**, **402**. When the bias voltage applied to the second electrode **110**, **402** increases, the voltage differential between the first electrode **106**, **404** and the second electrode **110**, **402** generates an electrostatic force that drives the first electrode **106**, **404** toward the second electrode **110**, **402**, thereby moving the mirror **102** toward the second electrode **110**, **402**. Additionally or alternatively, the amount of area of the second (e.g., base) electrode **110**, **402** that applies the bias voltage may increase, thereby increasing the electrostatic force and pulling the first electrode **106**, **404** closer to the second electrode **110**, **402**, such as in digital style electrodes. The electrostatic force decreases as the voltage decreases (and/or as the amount of area applying the voltage on the second electrode **110**, **402** decreases), thereby allowing the springs' restoring forces to move the first electrode **106**, **404** away from the second electrode **110**, **402**. In this manner, a controller **112** can control the voltage and/or amount of area applying a voltage on the second electrode **110**, **402** to control the position of the first electrode **106**, **404**, thereby controlling the position of the mirror **102**. The amount of travel of the mirror **102** corresponds to an achievable phase modulation of a device. Accordingly, examples described herein increase the travel distance of the mirror **102** in the MEMS pixel **100**, **400**, **410**, **420** without shortcomings of conventional MEMS pixels.

MEMS pixels include a pull-in point, also referred to herein as an instability point, corresponding to a maximum distance that the first electrode **106**, **404** can travel before a collapse occurs (e.g., before the first electrode **106**, **404** collapses toward the second electrode **110**, **402**, thereby destroying the pixel's functionality). The instability point is an equilibrium point, beyond which the system is potentially unstable. The stability of the system depends on the differential of the net force

$$\text{(e.g., } \left.\frac{dF}{dx}\right|_{x=x_e} < 0 \text{ stable equilibrium, and } \left.\frac{dF}{dx}\right|_{x=x_e} >$$

0 unstable equilibrium, where x_e is the equilibrium displacement). The net force is represented a combination of the electrostatic force and the spring force

$$\text{(e.g., } F = F_{electrostatic} + F_{mechanical} = \frac{\in A}{2(d-x)^2}V^2 - kx,$$

where E is the permittivity of the dielectric between the two electrodes, A is the Area of the base electrode, x is the displacement of the spring electrode **106**, **404**, and −kx is the restoring force in a linear spring). Accordingly, in that example, the first electrode **106**, **404** cannot maintain a position more than a d/3 threshold distance to the second electrode **110**, **402**. For example, if the spring electrode **106**, **404** is (without any electrostatic force applied) 900 micrometers from the base electrode, the spring electrode **106**, **404** may only travel 300 micrometers toward the base electrode before pull-in occurs. But examples described herein include techniques to operate the pixel **100**, **400**, **410**, **420** beyond the instability point without causing collapsing.

Conventional MEMS pixels include four attachments to anchor the first electrode (e.g., the spring electrode) to a surface. The first electrode of some conventional MEMS pixels includes four legs (having a spring constant) that attach to a rigid body. In this manner, when the electrostatic force increases, the legs stretch to allow the rigid body to move toward a base electrode. However, such a design increases the vertical stiffness of the springs, thereby requiring either: (a) increasing the voltage applied to the base electrode (e.g., wasting energy); or (b) increasing the size of the base and/or spring electrode (e.g., increasing the footprint and decreasing a packing factor). For example, conventional MEMS pixels require a bias voltage (e.g., the voltage applied by the second electrode) between 20 and 200 V to provide sufficient electrostatic force to move a conventional spring electrode **106**, **404**/mirror **102** to a desired position. Also, increasing the size of the electrodes limits the beam steering angle, limits the optical bandwidth, and limits the mechanical bandwidth. Examples described herein alleviate the power and size of such conventional MEMS pixels, by implementing the pixel **100**, **400**, **410**, **420** using only three attachments **108***a-c* to anchor the spring electrode **106**, **404**, thereby reducing the vertical stiffness by 25%. In this manner, the pixel size and bias voltage to control the position of the mirror **102** can be reduced. Also, some examples described herein include a spring electrode design (e.g., a hexagon-based design) that increases the perimeter-area ratio to further increase the efficiency of the MEMS pixel **100**, **400**, **410**, **420**. In examples described herein, a MEMS pixel sized below 10 micrometers can operate at a bias voltage of 10 V or less.

Some conventional pixels further reduce the number of anchors to only two support points. However, such conventional pixels make the MEMS design subject to tilt or rotation, due to process nonuniformities and/or deformation caused by thermal stresses or thin film deposition stresses. In examples described herein, these stresses are sufficiently compensated by described anchor design(s). Accordingly, examples described herein include very low tilt/displacement/rotation across process nonuniformities and environmental variation.

Also, some examples described herein include techniques to operate (e.g., move) the spring electrode **106**, **404** and the mirror **102** beyond the instability point without collapsing. In some examples described herein, the voltage applied to the base electrode is periodic (e.g., using a digital pulse or a sinusoid), corresponding to a distance beyond the instability point's d/3 threshold distance. Because the voltage corresponds to a distance beyond the d/3 threshold distance for a short duration of time, the first electrode **106**, **404** can travel up to a 9d/10 distance to the second electrode **110**, **402** without collapsing, thereby achieving a pixel travel that is nearly three times as far as conventional MEMS techniques relying on parallel plate electrostatic actuation. Because a sinusoid or pulse will cause the spring electrode **106**, **404** and the mirror **102** to vary distance in a pulse or sinusoid pattern, examples described herein include transmitting data related to the pulse or sinusoid (e.g., phase, amplitude) to a sampler of a receiving device, so that the sampler can sample the light beam corresponding to the desired distance of the mirror. For example, if the pixel **100**, **400**, **410**, **420** is periodic, such that the mirror **102** corresponds to a distance of 600 micrometers every 5 nanoseconds, the sampler can sample the light beam every 5 nanoseconds, so that the sampled light beam corresponds to the 600-micrometer distance of the mirror.

Also, some examples described herein include a mechanical design of the base **110**, **402** and/or spring electrode **106**, **404** to increase the d/3 threshold to a larger threshold (e.g., a 2d/3 threshold), without needing to sample the output by adjusting properties of the base and/or spring electrode **106**, **404**. For example, the base electrode **402** and the spring electrode **404** are curved away from each other (e.g., to progressively increase the distance d over position). For example, in such curved structures, the distance between the base **402** and the spring electrode **404** increases as the position along the actuating structure increases from the support structure. Adjusting (e.g., curving) the spring and/or base electrode changes the electrostatic and/or spring force from uniform, linear forces to non-uniform, non-linear forces. In this manner, when the spring electrode **106**, **404** approaches the curved base electrode, more force exists nearer to the anchor, and more restoring force exists at the spring (e.g., if the displacement is larger, then the spring's resistance is larger). The electrostatic force is inversely proportional to the square of the decrease in gap, when the restoring force of the spring is linear, as shown in Equation 1:

$$F_{es} = \frac{\in A}{2(d-x)^2} V^2 \qquad \text{(Equation 1)}$$

Such linearity can be compensated by progressively moving the biasing electrodes away from the weakest part of the spring, so the overall pixel travel increases from the d/3 threshold of instability to a larger (e.g., 2d/3) threshold of instability (e.g. twice the travel of conventional MEMS pixel travel) or greater. Also, this nonlinear attractive force can be balanced to increase the travel before reaching the instability, by pre-curving the spring (e.g., either through process induced stresses in the thin films, lithographic techniques, or other fabrication processes that create curved or sloped structures) to exhibit a nonlinear increase in mechanical stiffness (k) with increased displacement.

FIG. **5** is a block diagram of the electrode voltage controller **112** of FIGS. **1**A and **1**B described herein, to periodically vary the voltage applied to the base electrode **110** to periodically displace the spring structure **106** (e.g., and the mirror **102**) beyond the instability point corresponding to conventional MEMS pixels. While the electrode voltage controller **112** is described in conjunction with the pixel **100**, the electrode voltage controller **112** is useful to control a base electrode of any type of pixel. The electrode voltage controller **112** includes an example receiver **500**, an example mirror displacement determiner **502**, an example voltage source **504**, and an example transmitter **506**.

The receiver **500** of FIG. **5** receives instructions to move the mirror **102** of the pixel **100** to some distance from a computing device or circuit. Also, the receiver **500** determines when new instructions are received in order to trigger additional movement of the mirror **102**.

The mirror displacement determiner **502** of FIG. **5** processes the received instructions to identify the desired displacement distance of the mirror **102**/spring structure **106**. The mirror displacement determiner **502** determines whether the desired displacement distance of the received instructions is more or less than the instability point (e.g., the d/3 threshold distance corresponding to the instability point of conventional MEMS pixels). If the desired displacement distance is less than the instability point, the mirror displacement determiner **502** determines which voltage to apply to the base electrode **110** (e.g., for an analog based electrode) and/or how much amount of area of the base electrode **110** to apply a voltage to (e.g., for a digital based electrode). If the desired displacement distance is more than the instability point, the mirror displacement determiner **502** determines a periodic (e.g., a digital pulsing signal or a sinusoid) signal to apply to the base electrode **110**. In some examples, the mirror displacement determiner **502** determines, in response to the determined periodic signal, when the signal needs to be sampled to correspond to the desired displacement distance.

The voltage source **504** of FIG. **5** generates a voltage in response to the voltage determined by the mirror displacement determiner **502**. The voltage source **504** may capable of outputting a stable voltage and/or a periodic voltage. In some examples, the voltage source **504** may include two or more voltage sources (e.g., one for the stable voltage, and one for the periodic voltage). In some examples, the voltage source **504** is able to generate different periodic signals (such as corresponding to different frequencies, amplitudes, phases, etc.).

The transmitter **506** of FIG. **5** transmits data related to the periodic voltage (e.g., voltage varying data) and/or sampling data to a receiving device via a wired or wireless signal. The voltage varying data includes the phase, frequency, amplitude, etc. related to the voltage applied by the voltage source **504** and/or the phase, frequency, amplitude, etc. related to the movement of the mirror **102** (e.g., if they are not the same). In this manner, the receiving device can determine when to sample the receive signal so that the samples correspond to the desired mirror displacement position. The sampling data may include when to sample the received signal. In this manner, the receiving device can sample in response to the voltage varying data directly (e.g., without calculating when to sample the received light signal).

FIG. **5** shows an example implementation of the electrode voltage controller **112** of FIGS. **1**A and **1**B. Further, the receiver **500**, the mirror displacement determiner **502**, the voltage regulator **504**, the transmitter **506**, and/or more generally the electrode voltage controller **112** of FIG. **5** may be implemented by hardware, software, firmware and/or any combination of hardware, software and/or firmware. For example, any of the receiver **500**, the mirror displacement determiner **502**, the voltage regulator **504**, the transmitter **506**, and/or more generally the electrode voltage controller **112** of FIG. **5** could be implemented by one or more analog or digital circuit(s), logic circuits, programmable processor (s), application specific integrated circuit(s) (ASIC(s)), programmable logic device(s) (PLD(s)) and/or field programmable logic device(s) (FPLD(s)). In an example software and/or firmware implementation, at least one of the receiver **500**, the mirror displacement determiner **502**, the voltage regulator **504**, the transmitter **506**, and/or more generally the electrode voltage controller **112** of FIG. **5** include(s) a computer-readable medium (such as a hard drive, a memory, a digital versatile disc (DVD), a compact disc (CD), a Blu-ray disc, or other information storage device) that stores the software and/or firmware.

A flowchart representative of example machine readable instructions for implementing the electrode voltage controller **112** of FIG. **5** is shown in FIG. **6**. In this example, the machine readable instructions form a program that is processable by an instruction execution apparatus (such as processor **1112** shown in the processor platform **1100** described hereinbelow in connection with FIG. **11**) for causing the apparatus to perform the methods and processes described herein. The program may be embodied in software stored on a computer-readable medium, but the entire program and/or parts thereof could alternatively be executed by a device other than the processor **1112** and/or embedded in firmware or dedicated hardware. Further, although the program is described with reference to the flowchart of FIG. **6**, other methods of implementing the electrode voltage controller **112** may alternatively be used. For example, the order of execution of the blocks may be changed, and/or some of the blocks described may be changed, eliminated, or combined. Additionally or alternatively, any or all of the blocks may be implemented by one or more hardware circuits (such as discrete and/or integrated analog and/or digital circuitry, a field programmable gate array (FPGA), an application specific integrated circuit (ASIC), a comparator, an operational-amplifier (op-amp), a logic circuit, etc.) structured to perform the corresponding operation without executing software or firmware.

As described hereinabove, the process of FIG. **6** may be implemented by coded instructions (e.g., computer and/or machine readable instructions) stored on a computer-readable medium.

FIG. **6** is an example flowchart **600** representative of example machine readable instructions that may be executed by the electrode voltage controller **112** of FIGS. **1**A and **1**B to apply voltage to the base electrode **110**, **402** (of FIGS. **1**A, **1**B and/or **4**) to displace the spring structure **106**, **404** beyond the d/3 threshold distance (e.g., the instability point). Although the instructions of FIG. **6** are described in conjunction with the electrode voltage controller **112** FIGS. **1**A, **1**B and/or **5**, the instructions may be used by any type of electrode voltage controller in any type of pixel structure.

At block **602**, the receiver **500** receives instructions to displace the mirror **102** by X distance. As described hereinabove in conjunction with FIG. **5**, the instructions may be provided by another device to control the pixel **100** according to a desired output. At block **604**, the mirror displacement determiner **502** determines whether X is greater than a collapse threshold distance. The collapse threshold distance corresponds to the displacement distance that will cause the spring structure **106** to collapse (e.g., if held for more than a short duration of time). As described hereinabove, the collapse threshold distance is around d/3 where d is the distance of the spring structure **106** to the base electrode **110** when no voltage is applied by the electrode voltage controller **112**.

If the mirror displacement determiner **502** determines that X is not greater than the collapse distance threshold (block **604**: NO), the voltage source **504** applies a voltage to the base electrode **110** corresponding to the X distance (block **606**). In this manner, the spring structure **106** is pulled toward the base electrode **110** at the desired X distance. In some examples, the voltage source **504** may transmit a preset voltage to a portion of the area of the base electrode **110** corresponding to the X distance (e.g., corresponding to a digital base electrode). In such an example, to increase the displacement, the voltage source **504** may transmit the preset voltage to a larger portion of the area of the base electrode **110**. In other examples, the voltage source **504** may transmit a voltage to the entire area of the base electrode **110** corresponding to the X distance. In such an example, to increase the displacement, the voltage source **504** may transmit a higher voltage to the base electrode **110**.

If the mirror displacement determiner **502** determines that X is greater than the collapse distance threshold (block **604**: YES), the voltage source **504** periodically varies (e.g., using a digital pulsing signal or a sinusoid) the voltage applied to the base electrode **110** corresponding to the X distance (block **608**). In some examples, the voltage source **504** may generate the period voltage where the peak of the periodic voltage corresponds to the X distance. In other examples, the voltage source **504** may generate a preset periodic voltage, where the X distance corresponds to some point along the periodic voltage.

At block **610**, the transmitter **506** transmits voltage varying data and/or sampling to a receiving device (e.g., a device receiving the light reflected off the mirror **102** of FIG. **2**). The voltage varying data may include the frequency, amplitude, phase, etc. corresponding to the periodic voltage and/or the periodic displacement. The sampling data may include instructions corresponding to when to sample the received signal (e.g., the mirror displacement determiner **502** determines when the receive device should sample the received signal in response to the periodic signal and the desired X distance). In this manner, the receiving device knows when to sample the received signal so that the samples correspond to the desired X distance.

At block **612**, the receiver **500** determines whether additional instructions have been received corresponding to a new displacement distance. If the receiver **500** determines that new instructions have been received (block **612**: YES), the process returns to block **604** according to the newly received distance. If the receiver **500** determines that new instructions have not been received (block **612**: NO), the electrode voltage controller **112** continues to operate corresponding to the X distance until the receiver **500** receives a new displacement distance.

FIG. **7** is an example graph **700** illustrating the increased travel range generated by a harmonic resonant excitation waveform (e.g., a sinusoid or repeated pulse signal). The graph illustrates the change in normalized pixel displacement, according to frequency of the waveform for a first example mirror displacement **702** and a second example mirror displacement **704** of the mirror **102** of FIGS. **1**A and **1**B. The first mirror displacement **702** corresponds to a first modulation wavelength (e.g., 700 nanometers) and the example mirror displacement **704** corresponds to a second modulation wavelength (e.g., 470 nanometers). Alternatively, the first and second mirror displacements may be scaled to any fractional wavelength for any phase modulation by (a) adjusting the frequency of the drive pulses slightly off resonance and/or (B) reducing the amplitude of the bias voltage of the pulses.

As shown in the graph **700** of FIG. **7**, when the device is operated in high Q regime (Q>2), such as a packaged environment with low pressure the device can be resonantly pumped. As the drive frequency approaches the resonant frequency (e.g.,

$$f_{res} = \sqrt{\frac{k}{m}},$$

where k corresponds to the stiffness of the spring legs **202***a-c* of the spring structure **106**, and m corresponds to the mass of the mirror **102**), the pixel displacement of the first mirror displacement **702** can reach maximum displacements of an order of magnitude greater or more than when the bias signal has a period significantly below the resonant frequency. Accordingly, the scaling of the displacement can be more than an order of magnitude higher than the nominal displacement would be for the same voltage at a frequency below the resonant frequency. In this manner, the mirror **102** can be pumped at a low voltage (e.g., at or near the resonant frequency) to cause larger oscillations. The second mirror displacement **704** illustrates a scenario in which the bias amplitude is reduced to tune the peak amplitude for a different wavelength. A similar scaling effect can be achieved by periodically biasing slightly below the resonant frequency of the device. As shown in the graph **700**, the total travel of the mirror **102** is controlled while avoiding snap in (e.g., collapse). The achievable amplitude is a function of the quality factor of the pixel **100** and/or the sampling conditions. Although, each MEMS device may have different resonant frequencies proportional to its mass and/or stiffness, the graph **700** is designed with the overall system function in mind.

FIG. **8** illustrates an example demonstration **800** corresponding to a sampling of light reflected off the mirror **102**. The demonstration **800** includes an example pixel travel **802** of the mirror **102** that may be caused by a periodic symbol output by the electrode voltage controller **112** of FIGS. **1**A and **1**B.

The pixel travel **802** of FIG. **8** is a sinusoidal displacement representative of the variation of the mirror **102** in response to pulses and/or a sinusoid generated by the voltage controller **112** of FIGS. **1**A and **1**B. As shown in the demonstration **800**, the pixel travels over a range from 0 to λ/2, where λ is the wavelength of the modulated light. In some examples, the total distance may be scaled to achieve a desired fractional component of the wavelength by the pulse timing, the amplitude, the drive voltage, and/or the mechanical design of the pixel. Each displacement corresponds to a differentiation of the reflected light. Accordingly, a receiving device may sample the reflected output of the mirror at different points in time to correspond to different mirror positions. For example, the fast frame imaging each represent a different state that could be used for sampling. As described hereinabove, details of the periodic pixel travel **802** may be transmitted to the receiving device, so that the receiving device can sample according to a desired mirror position. In the demonstration **800**, the periods **1**, **2**, **3** and **4** represent different sampling points corresponding to different mirror positions. Accordingly, the mirror position may be sampled at appropriate times to achieve a desired fractional wavelength. In such a harmonic drive mode, the wavelength resolution is limited by complimentary metal oxide semiconductor (CMOS) imager timing procession. In some examples, mass or stiffness may be added/removed to the pixel design to adjust timing. All phase patterns may be captured within a single period, according to the application timing requirements, integrated circuit performance, frame upload bandwidth, and/or process uniformity. Additionally or alternatively, a frame may span multiple periods. Additionally or alternatively, averaging may be employed to compensate for pixel non-uniformity. Driving the device into resonance provides a large displacement without the need to exceed the pull-in voltage.

FIG. **9**A illustrates an example periodic signal **900** that may be output by the electrode voltage controller **112** to cause the mirror **102** to periodically vary beyond the d/3 instability point without collapsing. The example of FIG. **9**A includes the periodic signal **900** and an example mirror displacement **902**. Although the periodic signal **900** is a series of pulses with a particular period and pulse width, the periodic signal **900** may be any type of periodic signal.

The periodic signal **900** of FIG. **9**A includes equidistant pulses that repeat after 5 microseconds (e.g., 1/the resonant frequency), where the pulse has a width of roughly 1 microsecond. Alternatively, the periodic signal **900** may correspond any pattern. For example, the periodic signal **900** may be a function of the resonant frequency (e.g.,

$$f_{res} = \sqrt{\frac{k}{m}},$$

where both k and m will vary as a function of the specific dimensions, film thickness, and material set of the pixel design), and/or the period of the periodic signal **900** may be shorter or longer, according to the drive signal slew rate (e.g., a shorter, higher voltage pulse or a longer, lower voltage pulse). Outputting the periodic signal **900** results in the mirror displacement **902**. For example, when the pulse of the periodic signal **900** is high, the mirror **102** displaces toward the base electrode **110** of FIGS. **1**A and **1**B, such as

(−0.75)(the gap), where the gap corresponds to the distance between the base electrode **110** and the spring electrode **106** and/or the mirror **102**. When the pulse ends, the mirror displacement **902** illustrates that the mirror **102** displaces away from the base electrode **110** (e.g., (0.75)(gap)). Accordingly, the mirror displacement **902** illustrates the ability of the mirror **102** to be driven beyond the d/3 instability point without a catastrophic contact (e.g., without any risk of catastrophic contact). In some examples, the drive voltage could be reduced and the width of the pulse could be widened to achieve similar results. In such examples, pumping periods can be compensated by drive waveforms to improve the transition between states through active and passive cancellation via phase shifted waveforms and/or reset pulses. When the periodic signal **900** is used in an array of pixels, pixels can be addressed solely by phase shifted version of an identical drive source, as described hereinbelow in conjunction with FIG. **10**.

FIG. **9**B illustrates an example periodic signal **910** that may be output by the electrode voltage controller **112** to cause the mirror **102** to periodically vary beyond the d/3 instability point without collapsing. The example of FIG. **9**B includes the periodic signal **912** and an example mirror displacement **914**. The example of FIG. **9**B includes an example transition period **916** to transition between a first example pixel phase **918** and a second example pixel phase **920**.

As shown in the periodic signal **910** of FIG. **9**B, the electrode voltage controller **112** of FIGS. **1**A and **1**B may transition one or more pixels **100** from the first example phase **918** to the second example phase **920** to alter how light is reflected of the mirror **102**. In some examples, such as in an underdamped environment suitable for phase pumping, the transition period **916** may be necessary to quickly adjust from the first example phase **918** to the second example phase **920**. For example, the voltage controller **112** may apply one or more asynchronous pulses (e.g., reset pulses to slow the pixel travel and/or transition pulses to ready the pixel for the second example phase **920**) during the transmission period **916** to speed up the transition. In some examples, the voltage controller **112** may apply a transition across the pixel **100** and/or an array of pixels depending on the drive bandwidth. In some examples, several frames may be necessary to slow the pixel **100** before properly transmitting a second phase for a second image to the pixel **100** and/or pixel array.

FIG. **10** illustrates example phase shifted mirror displacements **1000** to generate example pixel array frames **1002** corresponding to example illumination states **1004**. The phase shifted mirror displacements **1000** includes four example mirror displacements **1006**, **1008**, **1010**, **1012** corresponding to four different delays. The pixel array frames **1002** includes four different frames **1012**, **1016**, **1018**, **1020** corresponding to four different pixel array states. The illumination states **1004** include four different illumination states **1022**, **1024**, **1026**, **1028**.

The shifted mirror displacements **1000** of FIG. **10** include four example mirror displacements **1006**, **1008**, **1010**, **1012**, each corresponding to a different delay. For example, the electrode voltage controller **112** may transmit different periodic signals corresponding to the different mirror displacements **1006**, **1008**, **1010**, **1012**. In some examples, additional circuitry may be included to generate the varying amounts of delay. In this manner, the electrode voltage controller **112** may output one periodic signal and a combination of a multiplexer and delay circuitry can facilitate movement of the mirrors of different pixels in an array corresponding to the mirror displacement **1006**, **1008**, **1010**, **1012**.

The pixel array frames **1002** of FIG. **10** include four different frames **1012**, **1016**, **1018**, **1020** that correspond to a four by four pixel array (e.g., including four mirrors at various displacement positions). For example, each of the pixels may correspond to any one of the mirror displacements **1006**, **1008**, **1010**, **1012**. Adjusting displacement of the different pixels of the pixel frames **1002** corresponds to the different example illumination states **1004**. For example, the first illumination state **1022** corresponds to the light reflected of the first example frame **1014**, the second illumination state **1024** corresponds to the light reflected of the second example frame **1016**, the third illumination state **1026** corresponds to the light reflected of the third example frame **1018**, and the fourth illumination state **1028** corresponds to the light reflected of the fourth example frame **1020**. Although, the example of FIG. **2** includes four pixel array frames **1002** corresponding to four shifted mirror displacements **1000**, any number and/or pattern of array frame may be used on any size pixel array. Additionally or alternatively, biasing waveforms can be scaled to achieve different displacements.

FIG. **11** is a block diagram of an example processor platform **1100** capable of executing the instructions of FIGS. **3**-**4** to implement the electrode voltage controller **112** of FIG. **5**. For example, the processor platform **1100** can be a server, a personal computer, a mobile device (e.g., a cell phone, a smart phone, a tablet such as an iPad™), a personal digital assistant (PDA), an Internet appliance, a DVD player, a CD player, a digital video recorder, a Blu-ray player, a gaming console, a personal video recorder, a set top box, or any other type of computing device.

The processor platform **1100** of the illustrated example includes a processor **1112**. The processor **1112** of the illustrated example is hardware. For example, the processor **1112** can be implemented by one or more integrated circuits, logic circuits, microprocessors or controllers from any desired family or manufacturer. The hardware processor may be a semiconductor based (e.g., silicon based) device. In this example, the processor implements the receiver **500**, the mirror displacement determiner **502**, the voltage source **504** and the transmitter **506**.

In this example, the processor **1112** includes a local memory **1113** (e.g., a cache). Also, in this example, the processor **1112** communicates with a main memory including a volatile memory **1114** and a non-volatile memory **1116** via a bus **1118**. The volatile memory **1114** may be implemented by synchronous dynamic random access memory (SDRAM), dynamic random access memory (DRAM), RAMBUS dynamic random access memory (RDRAM) and/or any other type of random access memory device. The non-volatile memory **1116** may be implemented by flash memory and/or any other desired type of memory device. Access to the main memory **1114**, **1116** is controlled by a memory controller.

The processor platform **1100** of the illustrated example also includes an interface circuit **1120**. The interface circuit **1120** may be implemented by any type of interface standard, such as an Ethernet interface, a universal serial bus (USB), and/or a PCI express interface.

In the illustrated example, one or more input devices **1122** are connected to the interface circuit **1120**. The input device(s) **1122** permit(s) a user to enter data and/or commands into the processor **1112**. For example, the input device(s) can be implemented by an audio sensor, a microphone, a camera (still or video), a keyboard, a button, a mouse, a touchscreen, a track-pad, a trackball, isopoint and/or a voice recognition system.

One or more output devices **1124** are also connected to the interface circuit **1120** of the illustrated example. For example, the output devices **1124** can be implemented by display devices (e.g., a light emitting diode (LED), an organic light emitting diode (OLED), a liquid crystal display, a cathode ray tube display (CRT), a touchscreen, a tactile output device, a printer and/or speakers). Accordingly, the interface circuit **1120** of the illustrated example usually includes a graphics driver card, a graphics driver chip and/or a graphics driver processor.

The interface circuit **1120** of the illustrated example also includes a communication device such as a transmitter, a receiver, a transceiver, a modem and/or network interface card to facilitate exchange of data with external machines (e.g., computing devices of any kind) via a network **1126** (such as an Ethernet connection, a digital subscriber line (DSL), a telephone line, coaxial cable, a cellular telephone system, etc.).

The processor platform **1100** of the illustrated example also includes one or more mass storage devices **1128** for storing software and/or data. Examples of such mass storage devices **1128** include floppy disk drives, hard drive disks, compact disk drives, Blu-ray disk drives, RAID systems, and digital versatile disk (DVD) drives.

The coded instructions **1132** of FIG. **6** may be stored in the mass storage device **1128**, the volatile memory **1114**, the non-volatile memory **1116**, and/or another computer-readable medium.

A computer program product is an article of manufacture that has: (a) a computer-readable medium; and (b) a computer-readable program that is stored on such medium. Such program is processable (e.g., executable) by an instruction execution apparatus for causing the apparatus to perform its operations described hereinabove. For example, in response to processing (e.g., executing) such program's instructions, the apparatus performs its operations described hereinabove, so that such operations are at least partially computer-implemented.

Such program (e.g., software, firmware, and/or microcode) is written in one or more programming languages, such as: an object-oriented programming language (e.g., C++); a procedural programming language (e.g., C); and/or any suitable combination thereof. In a first example, the computer-readable medium is a computer-readable storage medium. In a second example, the computer-readable medium is a computer-readable signal medium.

A computer-readable storage medium includes any system, device and/or other non-transitory tangible apparatus (e.g., electronic, magnetic, optical, electromagnetic, infrared, semiconductor, and/or any suitable combination thereof) that is suitable for storing a program, so that such program is processable by an instruction execution apparatus for causing the apparatus to perform its operations described hereinabove. Examples of a computer-readable storage medium include: an electrical connection having one or more wires; a portable computer diskette; a hard disk; a random access memory ("RAM"); a read-only memory ("ROM"); an erasable programmable read-only memory ("EPROM" or flash memory); an optical fiber; a portable compact disc read-only memory ("CD-ROM"); an optical storage device; a magnetic storage device; and/or any suitable combination thereof.

A computer-readable signal medium includes any computer-readable medium (other than a computer-readable storage medium) that is suitable for communicating (e.g., propagating or transmitting) a program, so that such program is processable by an instruction execution apparatus for causing the apparatus to perform its operations described hereinabove. In one example, a computer-readable signal medium includes a data signal having computer-readable program code embodied therein (e.g., in baseband or as part of a carrier wave), which is communicated (e.g., electronically, electromagnetically, and/or optically) via wireline, wireless, optical fiber cable, and/or any suitable combination thereof.

Accordingly, example methods, apparatus and articles of manufacture are described herein to increase efficiency and optical bandwidth of a MEMS piston-mode SLM. Examples described herein include a new spring structure for a MEMS pixel that is sized below 10 micrometers and can operate at a bias voltage of 10 V or less, while achieving significant displacements for light wave modulation beyond visible wavelengths. Also, examples described herein include a spring structure and/or a base electrode that is non-uniformly shaped (such as gray scale sloped, curved, etc.) to increase the instability point from a d/3 displacement distance (e.g., corresponding to conventional MEMS pixels) to a larger displacement distance (e.g., a 2d/3 displacement distance). Further examples described herein apply a voltage to a base electrode that is periodic (e.g., using a digital pulse or a sinusoid) to a voltage that corresponds to a distance above (e.g., away from) the d/3 threshold distance corresponding to an instability point. Because the voltage corresponds to a distance beyond the d/3 threshold distance for a short duration of time, the first electrode can travel up to a 9d/10 distance to the second electrode without collapsing, thereby achieving a pixel travel that is nearly three times as far as conventional MEMS techniques. Accordingly, examples described herein provide a sub-10 micron pixel that can modulate large light wavelengths (e.g. 1550 nm) with low drive voltage (e.g., 10 V).

Modifications are possible in the described embodiments, and other embodiments are possible, within the scope of the claims.

What is claimed is:

1. Apparatus to increase displacement of a mirror in a microelectromechanical system piston-mode spatial light modulator, the apparatus comprising:

an electrode with spring legs;

a base electrode;

a receiver configured to receive an instruction to displace the electrode by a displacement distance;

a mirror displacement determiner coupled to the receiver and configured to determine that the displacement distance is beyond an instability point of the electrode and to determine a periodic signal corresponding to the displacement distance; and

a voltage source to output a periodic voltage to the base electrode in response to the periodic signal, the periodic voltage to cause the spring legs to vary displacement of the electrode with respect to the base electrode according to the periodic voltage, the displacement including distances beyond the instability point.

2. The apparatus of claim **1**, further including a transmitter to transmit at least one of periodic voltage data or sampling data to a receiving device.

3. The apparatus of claim **1**, wherein the periodic voltage is to allow the electrode to displace beyond the instability point without collapsing.

4. The apparatus of claim **1**, wherein the periodic voltage is at least one of a digital pulsing signal or a sinusoid.

5. The apparatus of claim **1**, wherein, when the instruction is for a displacement distance that is less than the instability point of the electrode:

the mirror displacement determiner is to determine a stable signal corresponding to the displacement distance; and

in response to the stable signal, the voltage source is to output a stable voltage to the base electrode to cause the spring legs to displace the electrode to the displacement distance.

6. The apparatus of claim **1**, wherein the electrode is coupled to the mirror.

7. A method to increase displacement of a mirror in a microelectromechanical system piston-mode spatial light modulator, the method comprising:

determining a periodic signal corresponding to a displacement distance of an electrode of a pixel beyond an instability point of the electrode; and

outputting a periodic voltage to a base electrode in response to the periodic signal, the periodic voltage causing spring legs of the electrode to vary displacement of the electrode with respect to the base electrode according to the periodic voltage, the displacement including distances beyond the instability point.

8. The method of claim **7**, further including transmitting at least one of periodic voltage data or sampling data to a receiving device.

9. The method of claim **7**, wherein outputting the periodic voltage allows the spring legs to displace the electrode beyond the instability point without collapsing.

10. The method of claim **7**, wherein the periodic voltage is at least one of a digital pulsing signal or a sinusoid.

11. The method of claim **7**, further including:

when the displacement distance is less than the instability point of the electrode: determining a stable signal corresponding to the displacement distance; and, in response to the stable signal, outputting a stable voltage to the base electrode to cause the spring legs to displace the electrode to the displacement distance.

12. The method of claim **7**, wherein the electrode is coupled to the mirror.

13. A non-transitory computer-readable medium storing instructions that are processable by an instruction execution apparatus for causing the apparatus to perform a method comprising:

determining a periodic signal corresponding to a displacement distance of an electrode of a pixel beyond an instability point of the electrode; and

outputting a periodic voltage to a base electrode in response to the periodic signal, the periodic voltage causing spring legs of the electrode to vary displacement of the electrode with respect to the base electrode according to the periodic voltage, the displacement including distances beyond the instability point.

14. The computer readable storage medium of claim **13**, wherein the method includes transmitting at least one of periodic voltage data or sampling data to a receiving device.

15. The computer readable storage medium of claim **13**, wherein outputting the periodic voltage allows the spring legs to displace the electrode beyond the instability point without collapsing.

16. The computer readable storage medium of claim **13**, wherein the periodic voltage is at least one of a digital pulsing signal or a sinusoid.

17. The computer readable storage medium of claim **13**, wherein the method includes:

when the displacement distance is less than the instability point of the electrode: determining a stable signal corresponding to the displacement distance; and, in response to the stable signal, outputting a stable voltage to the base electrode to cause the spring legs to displace the electrode to the displacement distance.

18. The computer readable storage medium of claim **13**, wherein the electrode is coupled to a mirror.

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